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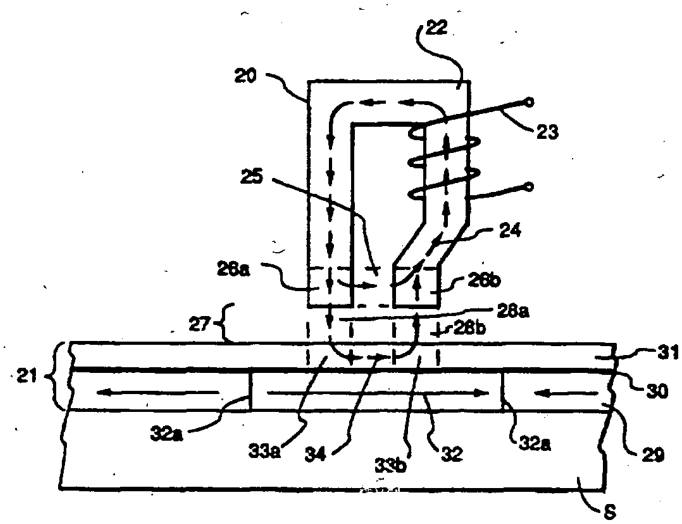

(57) Abstract

As depicted in the figure, the present invention comprises a transducer (20), having a permeable core (22) and a conducting coil (23), and a magnetic disk (21). Bias current in coil (23) drives a magnetic flux through magnetic circuit path (24). Air gap (25), having the lowest permeability in circuit path (24), provides the greatest reluctance to the flow of the magnetic flux. Magnetic disk (21) comprises a recording layer (29), a non magnetic exchange breaking layer (30), and a highly permeable shunt layer (31). The critical region in the present invention is variable reluctance gap shunt (34). The alternating magnetization levels in disk (21) change the reluctance of shunt (34), thereby modulating the bias flux in core (22) in transducer (20). This flux change allows for increased data storage density and data rates.

Specification

MAGNETIC RECORDING REPRODUCTION SYSTEM EMPLOYING A VARIABLE RELUCTANCE GAP SHUNT

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to the field of magnetic signal processing in which a magnetic medium with a high coercivity storage layer for recorded data is in motion relative to a magnetic transducer. In particular, the invention concerns a transducer and a magnetic storage medium, having in addition, a magnetically permeable layer(s) in near proximity to the storage medium, or in near proximity to the transducer. The region of the permeable layer(s) under the transducer gap, when influenced by a DC bias and/or a DC bias and an AC sense current through the transducer coils, functions as a variable reluctance gap shunt, which permits improved magnetic signal processing.

Brief Description of Prior Art

The introduction of ever more powerful hardware and software into the computer industry creates a need for increased storage density and data transfer rates in the storage devices used in computers. A recent trend has been to decrease the physical size of the storage devices, especially with Winchester-type hard disk drives and tape drives used for data backup. In the particular case of the hard disk drive, manufacturers have sought to reduce the physical spacing between the magnetic memory layer on the disk and the read/write transducer (head) to increase signal strength and signal-to-noise ratio. To the extent that this is achieved, the number of tracks per inch (TPI) and/or the linear recording density in bits per inch (BPI) can be increased to improve the recording areal density (TPI x BPI) and/or decrease the physical size of the device. The rate at which the data can be written to and retrieved from the storage medium has generally been limited by the speed at which the electronics could handle the binary data. The binary data is represented as a magnetic transition for a "1" and no transition for a "0", but some type of encode/decode scheme is used to insure that the transitions are optimally placed on

the recording medium to minimize the error rate and to provide timing pulses for data recovery.

Conventional saturated magnetic recording reproduction systems employ a magnetic recording medium consisting of a high coercivity (hard) magnetic layer (or layers) into which information is written by a transducer. The information that is written by the transducer is represented by a pattern of magnetization changes (reversals or transitions) in the magnetically hard layer(s). Reproduction of the recorded information is accomplished by a reproduction transducer (or read head) in which the alternating flux from magnetized regions of the magnetically hard medium is coupled through the core of the transducer so as to induce a voltage in a set of coils that surround the magnetic core of the transducer. Relative motion between the media and transducer is required for the recorded signal to be induced in the coils of the transducer. This signal is processed by a set of electronics called the channel. The majority of disk drives today use a Peak Detect (PD) channel with the data encoded and decoded by a 1,7 Run Length Limited (RLL) code. Some drives still use the less popular 2,7 RLL code. The even older MFM code, which is rarely used today, was a 1,3 RLL code.

For conventional saturated magnetic recording the transducer used for writing is often the same transducer used for reproduction. This need not be the case, but commonly is done in the recording industry for economic reasons. In the emerging reproduction system that uses a magnetoresistive (MR) element, the transducer (an inductive thin-film head) is used only for writing, and the MR element is used only for reading. The latter is placed in close proximity to the write head. The emerging trend in the industry is to use one of the Partial Response Maximum Likelihood (PRML) methods for electronic processing of the MR signal.

One of the problems with conventional saturated magnetic recording technology is that smaller and smaller spacing between the transducer and the recording media is required in order to increase the areal density and data transfer rate. Reduced head to media spacing produces higher reproduction signal strength resulting in improved short wavelength signal to noise ratio. Sharper pulses can also be obtained by the use of a narrower gap (with a possible penalty in efficiency) in the transducer. These improvements can be traded for either increased areal density and/or data transfer rate. The improvement afforded by the smaller head to media

spacing comes at a price. It requires an acceptable mechanical and tribological system that can cope with the reduced spacing. The required surface quality and finish of the recording medium becomes more and more difficult to achieve as the transducer and medium come into operational contact. This creates severe problems related to contamination, wear, and reliability. Also, the heads require detailed attention to narrower gaps, smoother surfaces, and more accurately constructed air bearing contours. In current disk drive recording systems, the clearance between the transducer and medium is only about 500Å to 750Å. Future technology seeks to further reduce this spacing as much as possible, in spite of the serious mechanical problems that must be solved to make contact recording successful. It is expected that the use of MR sensing at very low flying heights will allow a larger increase in areal density because of the higher read back sensitivity of the MR element compared with inductive thin-film heads for low relative velocity between the head and the media. This is particularly advantageous for small drives.

There are several problems involved with going to higher storage densities that must be overcome with both the conventional inductive and MR approach to magnetic recording. Previously mentioned are the physical problems associated with the manufacture of the recording disk media when the transducer is required to run in virtual contact. The extra research effort and materials development that will be needed to solve these problems could become an economic liability. Currently, the search for an alternate substrate is an active area of materials research. It is proving difficult to find methods for adequate surface finish. Additionally, deposition processes and the cobalt alloys used for the recording layer must be reevaluated.

In the MR technology, proper alignment between the read and write elements over the entire disk is a difficult mechanical problem which must be solved. The changing relationship between the write transducer and the MR read element causes severe demands on the servo tracking system. Also, potentially serious electrical signaling problems (noise) can occur if the MR element is allowed to contact the media during reproduction. The new PRML channels, while gaining some acceptance, are expensive when compared to the older PD channels and they consume more power. This makes them less acceptable for use in notebook and other portable computers where battery life is of extreme importance.

An alternative to reducing the physical spacing between the transducer and the recording medium is to make the recording reproduction system less sensitive to spacing loss. One such technique was developed by Ampex (B. Gooch et al., U.S. Patent 5.041.922 issued on 20 Aug 1991). It uses a keeper layer of highly permeable magnetic material placed on top of the normal recording layer. The transducer is biased with a DC current (preferred embodiment) during playback or reproduction. The patent teaches that the bias current creates a magnetic field in the keeper layer sufficient to saturate the keeper layer locally, under the head gap, thus forming a virtual transducer gap in close proximity to the recording medium. This virtual gap can be created by the use of either a DC or an AC bias current. The virtual gap serves to direct the flux from the written bit to the transducer core much the same as the physical gap in conventional recording. The patent claims that the normal read spacing loss is minimized because the flux from the bit being read can spread through the magnetically soft keeper layer and couple to the transducer over the entire region of its poles. Thus the flux from the written bit is more efficiently coupled into the head core, resulting in a larger signal for the same relative velocity between the medium and the head (or transducer) for the higher frequency recorded data.

Except for the more effective way the flux from the recorded bit is coupled into the transducer through the keeper layer, this improvement is in other respects similar to conventional recording. The transducer could be identical to that used in conventional recording, with a modification made in the electronics to apply the proper bias during reproduction. The flux from the written bit is coupled into the head core in the same manner as conventional recording. The encoding and decoding channels are compatible with the commonly used industry standards of 1.7 RLL and 2.7 RLL. The microelectronics circuits for these channels are the conventional ones available from many suppliers.

A possible disadvantage of this system is that the additional spacing, caused by the keeper layer, could reduce the efficiency of writing, depending upon the design of the head. Since the high write field essentially saturates the entire region of the keeper layer under the transducer, the layer takes on the magnetic properties of air, thereby increasing the effective transducer to media spacing. While this system offers some increase in recording density (Kao et al, abstract, IEEE

International Magnetics Conference. Apr 1993 and Sin et al. paper. IEEE International Magnetics Conference, Nov 1993) without significant increases in component costs, the industry has not adopted its use. This may be due to the perceived higher density gains anticipated to become available with the MR technology.

The recording industry presently depends upon the PD channel used with conventional media and transducers for most of the hard disk drive product that is shipped. However, this technology is approaching a limit set by the sensitivity of the inductive transducers and an ever lower signal to noise ratio as the track density is increased. The MR read head is more sensitive than the inductive head, but it is more expensive, not widely available, and works best with the higher power consuming PRML channels. The magnetic recording industry is in need of a simpler and more economical technology to reach its future goals of higher storage densities and increased data rates.

SUMMARY OF THE INVENTION

This invention provides the apparatus and method for creating a magnetic recording reproduction system employing a variable reluctance gap shunt. In general the apparatus includes an ordinary inductive head and magnetic disk (or magnetic tape), one or both of which contain a single layer or two or more thin laminations of highly permeable magnetic material placed in such a way as to be between and adjacent to either the disk and/or the head. Further the system provides, through its method of operation, a means to support the use of data codes and channels which cannot presently be used in conventional magnetic recording.

The invention further provides an effective method which permits useful utilization of the variable reluctance reproduction technique. The invention further provides for a selection of highly permeable magnetic materials having large permeability variation over the range of variation of the combined magnetic fields comprising the bias field and the field from the written transition (bit). Additionally, the method includes a technique by which the application of a bias field allows the system to support phase encoding and decoding of data. One object of this invention is to provide an improved apparatus and method for increased storage density and increased data rate.

A further object of the invention is to provide increased storage density and data rate, at the same transducer to medium separation as conventional recording, without significantly increasing the cost of the reproduction system.

Yet another object of the invention is to provide a recording reproduction technology that is more economical in its use of power than the PRML type electronic channels and MR heads.

Still another object of the invention is to provide a recording reproduction system which represents significant improvements over the system taught by U.S. Patent 5,041,922 ('922).

A further object of the invention is to enable the use of methods for encoding, storing and decoding data with respect to the magnetic recording medium which are not used in the current art.

Yet a further object of the invention is to enable the use of encoding and decoding methods for M-ary (M>2) data that results in increased data density and data rate. M=2 is for binary, 3 for ternary, 4 for quaternary, etc.

Further objects and advantages of the invention will become apparent from a consideration of the drawings and the following detailed specification.

BRIEF DESCRIPTION OF THE DRAWING

Fig. **1** is a schematic representation of the essential elements of an inductive magnetic transducer (head) and a magnetic recording medium illustrating the preferred embodiment of the present invention for longitudinal recording.

Fig. **1a** is a set of 3 highly schematic sketches illustrating the basic differences between conventional recording, the '922 system, and this new recording system.

Fig. **2** is a schematic representation of permeability vs magnetic induction for commercial 78 (78%Ni-22%Fe)Permalloy.

Fig. **3** is a schematic representation of how the permeability of the shunt varies across the region of the head pole tips and gap.

Fig. **4** is a schematic representation of the B vs H hysteresis loop for a typical low coercivity shunt material.

Fig. **5** is a schematic representation of the B vs H hysteresis loop for a typical high coercivity magnetic medium.

Fig. **6** is a schematic representation of the B vs H hysteresis loop for the films in Figs. **4** and **5** when they interact by magnetostatic coupling and by atom to atom exchange coupling at the interface between them.

Fig. **7** is a schematic representation of the B vs H hysteresis loop for the films in Figs. **4** and **5** when they interact by magnetostatic coupling, but not by atom to atom exchange coupling at the interface between them.

Fig. **7a** is a schematic representation of the B vs H hysteresis loop for a dual layer recording film with layers of slightly different coercivities, and a dual layer shunt film with layers of slightly different coercivities. The dual layer recording film and the dual layer shunt film interact by magnetostatic coupling, but not by atom to atom exchange coupling.

Fig. **8a** is a depiction of the equivalent magnetic reluctance circuit, elements of which are represented by the appropriate numerals of the corresponding elements from Fig. **1**.

Fig. **8b** is a schematic representation for the permeability vs field strength of a typical highly permeable shunt material, illustrating how the recorded transitions modulate the permeability of the gap shunt when a non-saturating DC bias current is applied to the transducer coil.

Fig. **8c** is a simplified schematic illustrating the basic origin of the readback signal phase shifts that occur for the variable reluctance mode of this invention.

Fig. **9a** is data showing the variation of the horizontal component of the magnetic field produced by various currents in the coil of a large-scale mock up of a head. The fields were measured in air and in a shunt layer made from cold rolled steel.

Fig. **9b** is data showing the measured variation of the horizontal component of the magnetic field for a large-scale mock up of a head, a shunt, and a set of permanent magnets representing recorded transitions. Data for several experimental conditions are presented.

Fig. **9c** is the theoretically predicted isolated pulse signal output obtained from a variable reluctance computer model using a DC bias of 1 mA applied to a 32-turn thin-film head.

Fig. **10a** is the experimental isolated pulse playback signal wave form obtained from an oscilloscope using a DC bias in the variable reluctance gap shunt mode.

Fig. **10b** is the experimental isolated pulse playback signal wave form obtained from an oscilloscope using no bias on a conventional disk with the same transducer as in Fig. **10a**.

Fig. **11a** is the experimental digit pulse string playback signal wave form obtained from a digitizing oscilloscope using positive and negative DC bias of 7 volts (0.7 mA) in the variable reluctance gap shunt mode.

Fig. **11b** is the experimental digit pulse string playback signal wave form obtained from a digitizing oscilloscope using positive and negative DC bias of 14.2 volts (1.42 mA) in the saturated "virtual gap" mode.

Fig. **11c** is a plot of normalized output voltage and phase of digit pulses as a function of the applied DC bias voltage. The disk medium consisted of a single recording layer with an exchange broken shunt of two laminated layers.

Fig. **11d** is a plot of normalized output voltage and phase of digit pulses as a function of the applied DC bias voltage. The disk medium consisted of a single recording layer with an exchange broken single shunt layer.

Fig. **12a** is a set of experimental digit pulse playback signal wave forms obtained from a digitizing oscilloscope illustrating the synchronous AC sense current reproduction mode.

Fig. **12b** is the playback signal from a digitizing oscilloscope illustrating the modulation of a 20 megahertz AC sense signal by isolated pulses recorded at a frequency of 1 megahertz.

Fig. **13** is a schematic representation of a system using Phase Shift Keying (PSK) modulation for data recording and reproduction according to this invention which allows time delays in transmission and reception of data.

Fig. **14** is a schematic representation of the essential elements of a magnetic transducer and magnetic medium illustrating a first alternative embodiment of the present invention.

Fig. **15** is a schematic representation of the essential elements of a magnetic transducer and magnetic medium illustrating a second alternative embodiment of the present invention.

Fig. **16** is a schematic representation of the essential elements of a monopole inductive transducer (head) and a magnetic medium illustrating the preferred embodiment of the present invention for perpendicular recording.

Fig. **17** is a schematic block diagram of a signal processing system which illustrates the implementation of several variable reluctance reproduction techniques.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Although the improved system of the present invention is similar in some basic design aspects to the Ampex '922 system mentioned above, it functions completely differently. In the present recording reproduction system, use is made of a **variable reluctance gap shunt**. The shunt consists of a single layer, or laminations of two or more thinner layers, of highly permeable magnetic material placed in near proximity to the recording layer. Near proximity in this context means that the highly permeable shunt layer(s) is close to, but not in intimate or direct (atom to atom) contact with the highly coercive recording layer(s), in order to avoid atom to atom exchange coupling between the different magnetic materials. When such exchange coupling is broken, a more effective shunting effect occurs. An exchange breaking zone, or a thin layer consisting of several atoms thickness, of a non magnetic material will usually suffice to permit the desired shunting effect. Shunting could still occur without the exchange breaking layer if the shunt were made very thick with respect to the recording layer; however, that type of structure is not an effective nor useful way to implement this invention since the write spacing loss would become large.

The details of the exchange coupling phenomenon is a complex quantum mechanical effect which has not currently been completely explained and understood. At distances on the order of several atoms thickness, the exchange force has been shown to be variable and probably periodic. In some material systems the exchange coupling is broken and recoupled several times within a distance of about a dozen atoms thickness of non magnetic spacing material. The existence of this unusual effect makes it difficult to accurately specify a required minimum thickness for an exchange breaking layer. This effect was discovered only recently, and it is commonly referred to as "biquadradic exchange". A good review paper containing useful references is available (J. Slonczewski, J. Appl. Phys. 73(10), 15 May 1993).

The bias, or sense, current (DC and/or AC) that is used during playback is adjusted in magnitude so that the region of the shunting layer below the transducer gap **is not fully saturated**. Therefore, **no saturated**, flux directing "virtual gap" is created adjacent to the recording layer, as taught by the '922 patent. Instead, the flux from the written bit in the recording medium is allowed only to modulate the permeability of the shunt material on the disk. The flux from the bit does not significantly leak out and couple into the transducer core. The modulation of the permeability in the shunt causes a **modulation of the reluctance** in the shunt region of the transducer magnetic circuit, as the recorded bit passes by the transducer gap. The bias level is adjusted to bring the reluctance of the shunt to a **non saturated** working point where it is most advantageously modulated by the flux from the recorded bit. The variation of the reluctance causes a variation of the flux created by the bias current in the head core, thus creating an induced playback signal.

In conventional recording no bias current is used during reproduction. The flux from the recorded bit is **directly linked** through the head core. In contrast, the **variable reluctance** reproduction system uses the recorded magnetic flux to **control or modulate the energy supplied by an external circuit**, which in this case is the flux in the head core generated by the bias or sense current. In his survey paper on flux-responsive reproduction heads, O. Kornei (Journal of the Audio Engineering Society, Vol 2, No. 3, July 1954) describes a group of recording systems under a heading he calls "control of external power". He states that while there are numerous possible designs, few are practical and many have only curiosity value. The present invention falls into that category of systems described by Kornei (1954) as those that control external power. In contrast, previous conventional recording systems use relative motion (mechanical energy) and flux linkage between the transducer and the medium to convert the flux changes into electrical energy.

In conventional recording without the keeper shunt, an AC bias applied to the head during reproduction results in a combined signal which is the simple sum of the AC bias signal and the reproduction signal from the recorded transitions. In contrast, in this new recording reproduction system, an unexpected result was found when an AC sense current was used during reproduction. Using the **variable reluctance** reproduction mode of this invention, the signal which results from applying a low level AC sense current during reproduction is a **modulation** of the AC sense signal

by the signal from the recorded transitions. If AC bias is used to create the saturated zone "virtual gap" in the keeper layer recording method taught in the '922 patent, the AC bias signal and the signal from the recorded transitions again simply add as in conventional recording. This modulation of the AC sense signal by the recorded transitions is a significant distinction between the **saturated keeper** recording method taught in the '922 patent, and the **partially saturated variable reluctance** reproduction system of the present invention.

Note that in the '922 patent the AC bias functions as an alternate way to create the saturated zone ("virtual gap") in the keeper layer in order to direct the flux from the recorded transition into the head core. The AC bias in that case is thus similar to the asynchronous AC bias commonly used during the write operation in tape recording to obtain better fidelity. In the '922 patent, the frequency is substantially higher than the data frequency. When applied during playback as taught by the '922 patent, the AC signal would be added to the signal from the recorded transition, but could be easily filtered off to restore the original signal. No particular synchronization or phase relation between the bias and the data was necessary or specified.

In the following drawings and descriptions, the unique attributes and details of the preferred and alternative embodiments of this invention will become apparent.

A magnetic recording reproduction system employing the variable reluctance technique of the present invention is shown schematically in Fig. **1**. As shown therein, it consists of a transducer **20** and a magnetic disk medium representation **21**. Transducer **20** consists of a permeable core **22** and a conducting coil **23**. The permeable core may contain magnetic flux created by a bias current in coil **23** which will follow a magnetic circuit path **24** in a direction depending upon the direction of the bias current. Transducer **20** includes a throat which comprises a gap region **25** and pole tip regions **26a** and **26b**. Transducer **20** and magnetic disk medium **21** are separated by the physical distance **27** referred to as the "flying height". The regions between the pole tips and the media are identified as **28a** and **28b** . These regions and gap region **25** have the lowest permeability (air) in the magnetic circuit, and offer the greatest reluctance to the flow of the magnetic flux created by the bias current.

In general, magnetic disk media consists of a substrate upon which layers of different materials are coated using widely accepted vacuum deposition techniques. Typically, a conventional disk media includes a substrate, a first layer of material (usually chromium) which serves to provide beneficial alignment to a second layer of high coercivity material (an alloy of cobalt), which functions as the recording layer. The recording layer is sometimes divided into laminations of two or more thinner layers separated by thin layers of non magnetic material. If multiple recording layers are used, they may consist of different alloys of cobalt. Laminating the recording layer has been shown to reduce the level of media noise in the reproduction signal by a factor of the square root of the number of laminations. The last (top) layer of a conventional disk is usually a thin layer containing carbon which functions to protect the recording layer from wear due to head contact.

In Figure **1**, a simplified magnetic disk medium representation **21** depicts only a single recording layer **29**, a non magnetic exchange breaking layer **30**, and a highly permeable magnetic shunt layer **31** of low coercivity material. For clarity, the alignment chromium layer and the carbon protective layer normally included with the substrate S are not shown. Magnetic shunt layer **31** preferably consists of at least two thin laminations, the separation again being omitted from the figure for clarity. Lamination of the shunt layer helps to reduce Barkhausen noise in a manner similar to that afforded by the laminated structure of audio heads. The bold arrows **32** represent magnetically saturated regions in the recording layer. The boundaries **32a** between regions of opposite magnetic saturation are transitions (the binary representation of a "1"). Regions **33a** and **33b** represent the regions of the shunt layer **31** where the flux, generated by a bias current through coil **23**, couples with the disk medium. Region **34** is the **variable reluctance gap shunt**, a region directly below and aligned with physical gap **25** of the transducer. Regions **33a**, **34**, and **33b** are depicted in Fig. **1** as distinct regions with sharp boundaries. This is a simplification for clarity.

Fig. **1a** illustrates in a highly schematic way the basic differences between a conventional recording system, the system taught by the '922 patent, and this new recording system. Sketch **A** shows a convention recording system during playback mode. Essential elements of the system are numbered consistently with those from Fig. 1. In addition, magnetic field lines **210** are shown emanating from written

transitions **32**. In this conventional recording system, field lines from the recorded transition couple with transducer 20 and through coil **23** to induce a voltage in the coil as the transducer moves from one transition to the next. Sketch **B** illustrates the system taught by '922. A keeper layer **31** captures magnetic field lines **210** and prevents them from coupling with transducer 20 until a bias current is applied to coil **23** by a DC source **211**. This bias current produces a bias magnetic field designated by dashed lines **212**. The fringing flux from the bias field is of sufficient magnitude to totally saturate a region of keeper layer **31**, which allows the magnetic field from the transition to leak out and couple into transducer 20 and through coil **23** in similar fashion to the conventional system in sketch **A**. In this new recording system illustrated in sketch **C**, a DC bias current is applied to coil **23** by DC source **211**, or a DC bias plus an AC sense current from **213** is applied to coil **23**. In either case the magnitude of bias magnetic field **212** is small enough that the respective region of keeper layer **31** is not saturated. Field lines **210** remain keepered in layer **31** and do not significantly leak out and couple with transducer 20.

The present recording system is distinct from that of the '922 patent in that it operates in a different permeability(μ) regime of the shunt, and utilizes a different recording principle. A simplistic representation of this principle is illustrated in Fig. 2, which shows the variation of the permeability vs. magnetic induction (B field) for commercial 78 Permalloy as given by R. Bozorth ("Ferromagnetism", D. Van Nostrand Co., Inc., p128, 1951). This curve describes the response of the material to DC and low frequency magnetic fields. Typical recording frequencies are in the megahertz range, and permeability data for most materials is largely unavailable for frequencies above a few kilohertz. Therefore, the low frequency curve will be used here to illustrate the basic principle of operation, even though the curve is not accurate in the strictest sense.

It is well known that the permeability of a magnetic material is a nonlinear function of the magnetic induction, and its value depends upon many factors. Some of the more important factors are chemical composition, grain size, annealing history, magnetic induction, stress, and physical shape. In general, the permeability of a material consists of both real and imaginary parts, i.e. $\mu = \mu' + j\mu''$ where μ' is the real part, μ'' is the imaginary part, and $j = (-1)^{1/2}$. Usually, μ'' is zero at DC and low frequencies for a given level of magnetic induction, and can become large near

resonance at some higher frequency. Beyond resonance, μ'' again approaches zero and μ' approaches unity (1), i.e. the material no longer responds to a magnetic field. For many highly permeable materials that may be used with this invention, some resonance behavior may be present at the highest data frequencies and AC sense current frequencies of interest. This would enormously complicate any detailed explanation of the observed effects, since the necessary data is unknown and depends upon many variables, including the physical geometry. The best procedure is to judge a particular material by the results of its use in recording experiments. The following explanation of the variable reluctance principle is somewhat simplistic, but is adequate to illustrate the basic idea.

In zone **35** of the permeability curve of Fig. **2**, the shunt is far from saturation, and the permeability rises to a maximum as the magnetic field density in the material increases. In zone **36** the shunt begins to approach saturation, and the permeability decreases rapidly as the magnetic field density in the shunt material increases. In zone **37** the shunt is essentially saturated, and the permeability changes slowly as the magnetic field density in the shunt material continues to increase. In zone **37** the permeability approaches that of air, and if operated here, element **34** (of Fig. **1**) would act magnetically as if it were replaced by a physical air gap. Patent '922 teaches operation in zone **37** by saturating the keeper (shunt) and creating a "virtual gap" in the shunt material and adjacent to the recording layer. In that mode, the flux from the written transition under the "virtual gap" in the shunt layer is able to leak out and couple into the head core similar to the situation in conventional recording.

The recording reproduction system of the present invention uses a bias level appropriate for operation along the segment of the curve in zone **36** that has the steepest slope. Here small changes in the magnetic field strength in the shunt material, caused by the transition, lead to relatively large changes in the permeability of the shunt, and accompanying changes in the total reluctance of magnetic flux circuit **24** of Fig **1**. Flux from a written transition **32a** serves to modulate the permeability of the shunt. Essentially, the flux does not leak out to couple with the head, as it does in conventional recording and in the '922 patent. The bias is selected to place the operating point on the steepest slope segment of the curve in zone **36**, where the varying flux across the written transition causes the greatest

variation in shunt permeability or shunt reluctance. Operation in zone **35** is not desirable because the possible range of permeability variation is reduced for most shunt materials. Operation around the peak region of the curve could lead to double values for the permeability, read back signal inversion, and a smaller range of permeability variation. In addition, after data has been written to the recording media, the magnetic flux from the magnetized regions provides a DC bias to the shunt layer that effectively keeps the operational point from being in zone **35**, unless the shunt layer is made significantly thicker than the optimum thickness for effective shunting. In the case of the shunt being thicker than optimum, the bias could be increased enough to bring the operating point back to the steepest slope segment of the curve in zone **36**.

The permeability characteristics of the variable reluctance shunting region are shown in Fig. **3**. Region **38** represents the permeability associated with region **34** (in Fig. **1**) when the head gap is over a region of the recording medium that does not contain a magnetic transition. Regions **39a** and **39b** correspond approximately to the regions under the pole tips, **33a** and **33b** of Fig. **1**. Until a recorded transition (bit) is approached and passed, the values of the permeability across elements **33a**, **34**, and **33b** remain approximately as shown by regions **39a**, **38**, and **39b** in Fig. **3**. The permeability across these regions is determined by both the magnetic field from the recorded bit and the magnetic field from the bias current applied to the transducer. The boundaries between the regions are not perfectly sharp, but rather correspond to zones where the permeability changes in response to the bias field from the head. Fig. **3** illustrates that the operating point is chosen such that the shunt in region **38** is not fully saturated, i. e. the permeability is much greater than one. When a transition passes the gap, the permeability in region **38** changes in response to the changing magnetic field strength at the transition. However, the bias is chosen such that the entire range of permeability change for region **38** remains in zone **36** of Fig. **2**.

Magnetic medium **21** (Fig. **1**) must possess certain characteristics to be useful in this reproduction system. An important trait relates to the effectiveness of the shunting layer(s), which was previously described as being greatly improved with the breaking of magnetic exchange by layer **30** between the high coercivity recording layer (medium) **29** and the highly permeable shunting layer **31**. This characteristic

of the media is described and given an operational definition by reference to Figures 4 through 7a.

Figure 4 depicts schematically the B vs. H hysteresis loop for a layer of highly permeable magnetic shunt material. Level **40** corresponds to the magnetization saturation of the material, which is the product of the layer thickness and the magnetic saturation of the alloy composition (commonly referred to as M_ST). Point **41** is the value of the H field that represents the coercivity of the material. Adequate candidate magnetic shunt materials should possess coercivities in the range of 0.1 to 200 Oersteds and preferably 0.1 Oersteds to a few tens of Oersteds. In thin film form the coercivities of permeable materials are generally larger than in bulk form, and they depend in part upon the thickness of the material. So while very low coercivities may be desirable, they may be difficult to achieve in practice. Note that even if the shunt material is composed of two or more equal thickness layers separated by thin layers of non magnetic material, the B vs. H hysteresis loop will retain the characteristic of Fig. **4** as long as each layer has the same coercivity. If one of the individual layers differed somewhat in coercivity (and thickness) from the other layers, then the B vs H hysteresis loop would show a slight coercivity discontinuity corresponding to the slightly different value of H that caused the magnetization in that layer to switch directions.

Figure **5** represents schematically the hysteresis loop of a high coercivity longitudinal recording material as used for medium **29** in Fig. **1**. Level **42** is again the magnetic saturation which may (for example) be approximately the same as that of the shunt layer. Point **43** is the value of the H field that represents the coercivity of the material. This coercivity is far greater than that of the shunt material, typically between a thousand and two thousand oersteds or more for media in use today. As discussed previously for the highly permeable layer, this high coercivity layer may also be divided into two or more layers separated by non magnetic layers. If the individual layers have the same coercivity, the B vs H hysteresis loop will still have the form shown in Fig. **5**. If one layer has a coercivity slightly different from the others, then the B vs H hysteresis loop will show a small discontinuity corresponding to the relative difference in coercivity.

If a **single** shunt layer, with a B vs H loop as shown in Fig. **4,** is placed in direct intimate (atom to atom) contact with a **single** recording layer, with a B vs H

loop as shown in Fig. **5**, the composite layer will have a B vs. H hysteresis loop as shown in Fig. **6**. The saturation level **44** will be approximately the sum of levels **40** and **42**. The coercivity at point **45** will be greater than that at point **41** but less than that at **43**. The composite material, made by the two layers placed in direct contact, will act magnetically like a single material within the ranges of thickness of interest for magnetic recording. However, if the intimate atom to atom contact between the layers is interrupted by a non magnetic layer (consistent with the previous discussion about the quantum mechanical complexities of its exact specification for small distances), the composite magnetic hysteretic response will possess distinguishable characteristics of each material. This result is shown in Fig. **7**. The saturation level **46** remains the same as **44**, but the coercivity point **47** is now substantially the same as **41**, and coercivity point **48** is substantially the same as **43**. This means that the two layers are reacting substantially independent of each other to the applied H field.

If the shunt layer and the magnetic recording layer are each made of multiple layers with non magnetic separation layers, the result shown in Fig. **7** will still occur if the coercivities of the multiple shunt layers are equal to each other, if the coercivities of the multiple recording sublayers are equal to each other, and if the recording top layer that is nearest the bottom shunt layer is separated from it by a non magnetic layer. Slight discontinuities would be discernible in the respective high and low coercivity regions of the B vs H hysteresis loop, if the layers comprising each region were of slightly different coercivities. A simple example of a B vs H hysteresis loop for layers with different coercivities is shown in Fig. **7a**. The shunt layer now consists of two layers, one with original coercivity **47** and one with lower coercivity **47a**. Also, the recording layer consists of two layers one with original coercivity **48** and one with lower coercivity **48a**. Many variants of this basic concept are possible. The important trait for media for use with this invention is that the permeable layers be able to react independently of the recording layers to the applied H field in a B vs H hysteresis loop measurement. The layers will interact magnetostatically, but will not interact through atomic exchange coupling.

For the purpose of this invention, magnetic media with a shunt layer should react to an applied H field in substantial likeness to the response depicted in Fig. **7**, slight differences caused by coercivity variation in multiple layers, and quantum mechanical complexities of defining small spacing, not withstanding. However, it

is not necessary that the two different types of magnetic material have the same level of saturation magnetization thickness. Some amount of difference can be readily tolerated. In the figures, equal levels of saturation magnetization thickness were used as an example merely for convenience. Saturation level **40** (Fig. 4) of the shunt layer(s) and **42** (Fig. 5) of the recording layer(s) need not be identical. What is important is that the shunt layer be thick enough to shunt the flux from the recorded signal enough to permit operation in zone **36** of the permeability vs field strength relation shown in Fig. **2**. In general, the difference in the average coercivities of the recording layer(s) and the permeable layer(s) should be large enough that the bias current used on the transducer during reading does not disturb the recorded data in the recording layer. Since the trend in current media development is toward higher coercivity, this is not anticipated to be a problem.

While the above detailed media description has been presented utilizing a longitudinal recording layer(s) as an example, it will be appreciated that this recording system is also useful if a perpendicular magnetic recording layer(s) is substituted for the longitudinal recording layer(s). The perpendicular medium also must be constructed in such a way that the magnetic exchange between the shunt layer(s) and the perpendicular recording layer(s) is broken to the extent that the shunt and the recording regions are able to react substantially independently of each other to an applied magnetic field. Conventional perpendicular magnetic media usually contain a relatively thick layer(s) of permeable magnetic material positioned on the side of the recording medium opposite the transducer (i.e. under the recording layer proximate the substrate). This layer(s) acts both as a keeper for the written vertical transitions, and as a flux return path for a monopole transducer during the reading and writing of data. In this case a non-magnetic layer between the media and the permeable layer, as well as laminations of the permeable layer, can be used to improve media performance (for example Sugita, U.S. Patent 4,687,712 issued 18 Aug 1987). For the purpose of this invention, perpendicular media preferably with a keeper layer under the recording layer can be used, provided the shunt layer(s) placed on top of the media is substantially exchange broken from the recording layer(s) as previously described for the case of longitudinal recording media.

The operation of the reproduction system can be schematically described by a simplified equivalent magnetic reluctance circuit as depicted in Fig. **8a**. The

reluctive elements in the circuit are labeled by the numerals from Fig. **1** which correspond to each part of the magnetic circuit along flux path **24**. For a reluctive element, the reluctance is given by the length of the element divided by the product of the permeability and the cross-sectional area of the element. This is completely analogous to the definition of resistance for an electrical element, and the circuit is analyzed as the magnetic equivalent of Ohm's law for electrical circuits. A magnetomotive force, represented by the letters MMF enclosed in a circle, is provided by a bias current in coil **23** of Fig. **1**. The total magnetic flux in the head core, φ_t, is the sum of the flux, φ_g, in the loop containing gap element **25** and the flux, φ_s, in the loop containing the variable shunt reluctance element **34**.

As the flux from a written transition varies the reluctance in shunt **34**, the total flux, φ_t, varies in accordance with the solution for the magnetic flux circuit shown in Fig. **8a**. The variation of the reluctance in element **34** modulates the flux in the transducer core which is supplied by the bias current. The time varying flux in the transducer core induces a voltage signal in coil **23** that is proportional to the number of turns of the coil and the time rate of change of the magnetic flux.

The preferred mode of operation is to use an AC sense current (or AC plus DC bias), but since that representation is more complex to model and explain, the more tractable case of DC bias will be demonstrated first to clarify the basic principles. Initially, the recorded transitions will be assumed to be far enough apart that they are essentially isolated from each other, so that their mutual interaction, called inter-symbol interference, can be ignored.

The permeability vs field strength for the typical shunt material that was given in Fig. **2** is again referred to in Fig. **8b** for the demonstration of DC bias. Based upon the nature of permeability previously discussed, this permeability curve is probably adequate for DC bias. However, when the recorded transitions pass the transducer gap at a frequency of a few megahertz, the permeability curve may have a different shape appropriate to the higher frequency, and non-linear effects may be more pronounced. The bias current is adjusted to create a shunt flux φ_s in the magnetic circuit of Fig. **8a** sufficient to bring the operational point of the variable reluctance gap shunt **34** (of Fig. **1**) to point **49** in zone **36** of Fig. **8b**. The spatially averaged value of the flux in the gap shunt, when it is between the transitions in the

recorded data, is approximately constant (since the transitions are well isolated). However, there are two values of flux depending upon the direction of the bias flux and the direction of the flux generated from the magnetized regions of the recorded data.

In one case, the bias flux is in the same direction as the flux in the gap shunt that is generated from the written bit, in the other case it is opposite to it. If the bias flux is opposed to the flux in the shunt from the written bit, there is some small but finite volume of the shunt where the flux level must pass through zero. If the bias flux is in the same direction as the flux in the shunt, the flux level does not have to pass through zero. Therefore, there are two values of the spatially averaged flux in the shunt, and they alternate as each transition passes through the shunt region under the transducer gap. The difference in the two values of the spatially averaged flux is probably small, perhaps on the order of a few hundred gauss. In Fig. **8b** a larger change in flux level, about a thousand gauss at this scale, is used for the convenience of a clearer illustration.

Beginning at magnetic field level **50** and proceeding in the direction indicated by the arrows., the effect upon the permeability of two successive transitions is described. Initially, the flux in the shunt from the recorded bit is opposed to the direction of the DC bias flux. This causes the spatially averaged value of the magnetic field in the gap shunt to be offset from bias level **51** to level **50**. As the first transition passes the gap shunt, the field from the recorded bit reverses direction, being now in the same direction as the bias field. The field in the shunt passes back through bias level **51** and reaches level **52**. The flux from the bit is now in the direction of the flux from the DC bias. While this field change takes place in the gap shunt, the average permeability of the shunt goes from level **53** through level **54** to level **55**. The field in the shunt then stays at level **55** until the next transition passes the gap. At that time the sequence repeats in reverse order, with the field in the shunt switching back to level **50**, and the permeability switching back to level **53**.

The rate of change of the field in the shunt is maximum when it passes through bias level **51**. Likewise, the rate of change of the permeability of the shunt is maximum when it passes through level **54**. Correspondingly, the rate of change of the reluctance is also maximum, and the peak of the reproduction pulse occurs at this time. The field in the shunt and the permeability of the shunt are in phase.

However, they do not cross their respective operational points (**51** and **54**) at the same time that the transition, which was originally written in the high coercivity recording layer, is centered on the transducer gap shunt. The pulse that is detected by the variable reluctance gap shunt is either earlier than or later than the time that the recorded transition is passing under the gap. The magnitude of this timing or phase shift is dependent upon the level of the DC bias and its direction with respect to the magnetization of the recorded bit. Data on this phase shift aspect will be described later.

The basic nature of the origin of the phase shift in the signals can be understood with reference to Fig. **8c**. This figure shows a series of three simple schematic representations of the interaction of the variable reluctance zone sense fields with the fields in the shunt layer on the media. In each schematic representation, indicated by the Roman numerals I-III, a small portion of a recording medium is depicted at **21**, consisting of recording layer **29**, exchange breaking layer **30**, and shunt layer **31**. These elements are labeled consistently with their corresponding elements in Fig. **1**. The bold arrows labeled **200** correspond to the magnetic flux generated by magnetized areas in the recording layer and their paths with respect to transition boundary **201** and shunt layer **31**. The position of the transition boundary in the shunt layer is indicated as dashed line **202**. Dashed line **203** represents the approximate path of the sense flux generated by the sense current in the transducer, and the direction of the flux is indicated by arrow **204**.

In schematic **I** the sense flux is large enough to saturate the shunt layer and the flux from the magnetized recording layer leaks out and couples directly with the transducer core (not shown). At the transition boundary the flux (**200**) closes on the side initially indicated as open and opens on the opposite side. This change in flux in the transducer core induces output pulse **205** in the reproduction system, and the pulse occurs exactly at the position of transition boundary **201** in recording layer **29**.

In schematic **II** the sense flux is only large enough to allow operation in the variable reluctance mode. The flux from the magnetized regions of the medium does not leak out and couple with the transducer core. The direction of the sense flux, indicated by **204**, is in the same direction as flux **200**. If the transducer were not positioned near the transition, position **202** would be aligned with position **201**. When the transducer is near the transition, the direction of magnetization in the shunt

is such that it attracts or pulls transition **202** in the shunt layer toward it. The reluctance in the region under the transducer pole tips switches when the transducer is centered on position **202** and before it reaches position **201**. This results in output pulse **205** coming earlier than expected in conventional recording by an amount Δ.

In schematic **III** the direction of the sense flux is reversed with respect to that previously described. Now the direction of the sense flux, indicated by **204**, is opposite to that of flux **200**. The direction of the magnetic poles are now such that transition position **202** in the shunt layer is pushed ahead of the approaching transducer. This causes the output pulse to be detected later than expected in conventional recording by the amount Δ. For a given recording medium and its material properties, the size of Δ will depend upon the magnitude and direction of the sense flux created by the sense current in the transducer.

In order to verify the description given above, a large-scale mock up of a head and recording medium was constructed. The head core was made from cold rolled steel and was 6 inches long by 4 inches high by one inch thick. The one inch thickness corresponded to the recording track width. A 3/16 inch wide gap was provided at the center on one side of the 6 inch length. On the other side of the 6 inch length a coil for applying a DC bias current was included which consisted of 250 turns of #18 transformer wire. The recorded bits were simulated by 12 neodymium-iron-cobalt magnets placed end to end along a line with like poles alternately facing each other. The magnets were one inch wide to correspond to the head width and nearly one inch long. This simulated a string of isolated pulse transitions that completely covered the length of the pole tips of the head. The magnet holding fixture was equipped with a large micrometer screw to accurately move and measure the placement of the head with respect to the magnets (bits). Two shunts were constructed of cold rolled steel and contained small holes to accept a probe for field measurements. One had a thickness of 1/4 inch and the other had a thickness of 1/2 inch. The exchange breaking layer was simulated by a layer of aluminum 0.050 inches thick, and although not necessary for a macroscopic demonstration, it provided protection for the magnets and a layer for lubrication to facilitate movement of the head. Magnetic field measurements were made with an FW Bell Model 9500 Gauss meter equipped with an STM 99-0404 standard transverse Hall effect probe.

An extensive amount of data was taken using both shunts and various bias currents. In summary, it was found that the 1/4 inch thick cold rolled material provided an adequate level of shunting. The measurement probe was placed in a small machined hole in the center of the 1/4 inch shunt thickness and aligned with the head gap. Magnetic flux measurements were made with and without bias current in directions both horizontal to and perpendicular to the plane of the magnets. For the initial calibration, measurements as a function of bias current were made both in air and in the 1/4 inch thick shunt layer. For these measurements the head was spatially separated from the magnets to avoid their influence.

The results of the calibration measurements for the head are given in Figure **9a** for the horizontal component of flux generated by various bias currents measured at gap center and 1/8 inch below the level of the pole tips. The curve labeled **56** is measured in air, and it corresponds to the usual fringing field for a head. The curve labeled **57** is measured in the 1/4 inch thick cold rolled shunt material at approximately the same relative position with respect to the head gap. The levels of flux given by curve **57** are not the true flux levels in the shunt material, but are the fields that fringe across the opening for the probe. Most of the flux is shorted around the opening through the available lower reluctance path. The flux levels measured are therefore related to the true levels in the material by some constant ratio related to the permeability of the cold rolled steel with respect to air, and to the geometry of the system. It is clear that the shunt material is not saturated by DC bias currents up to 4 amperes because curve **57** is not rolling over in classic saturation behavior. Also, curve **57** is approximately symmetrical but offset with respect to zero bias by about -0.5 amperes, and with respect to zero field by about -50 gauss. This is due to a small amount of residual magnetization in the steel. Since the steel is not saturated by bias currents up to 4 amperes (~1000 gauss), and since the saturation level of steel is about 20,000 gauss, the constant factor which relates the measured flux levels to the true flux levels in the steel must be less than 20 (i.e. 20,000/1000). Considering the influence from the geometry, it is probably much less than 20.

The essential data from these large scale experiments is summarized by the curves given in Fig. **9b**. For all cases the measurement probe was positioned to measure the horizontal component of the magnetic field as the head was positioned

along the magnets (bits) by the micrometer screw. A data point was recorded every 0.05 inches, and the total length of head travel was sufficient to cover one negative and one positive region of magnetization. There was no relative motion between the head and media during a measurement; therefore, the data represents only the static interaction of the fields. The measurements begin in a region of positive magnetization just before a first transition to a region of negative magnetization in the shunt, proceed past a second transition, through a positive region of magnetization, and end just past a third transition in the next region of negative magnetization. The specification of the direction of magnetization at the start of the measurements is arbitrarily selectable.

The curve labeled **58** was made with the 1/4 inch shunt replaced by a 1/4 inch non magnetic aluminum spacer with no bias current applied to the head coil. Points **58a**, **58b**, and **58c** are the positions at which the field goes to zero, therefore marking the exact positions of three successive transitions. Curve **59** was made with the 1/4 inch cold rolled steel shunt in place, but **without** any bias current applied to the head coil. Clearly, the presence of the highly permeable material reduces the measured fields with respect to those for curve **58**, because of the lower reluctance path around the probe aperture. Note that the points of zero crossing are shifted to somewhat lower values of relative position with respect to points **58a**, **58b**, and **58c**. This is caused by the steel acquiring a low value of permanent magnetization which results in a small offset in one direction.

When a DC bias current is applied to the head coil, curve **59** is transformed into either curve **60** for a bias of -1.1 amperes, or curve **61** for a bias of +1.1 amperes. Similar to conventional recording models, the way that the field changes across a transition can be described by an arc tangent function and a characteristic transition width parameter. The parameter describes the steepness of the slope change of the field with position across the transition. The slope changes for curve **58** (no shunt) appear, in general, to be less than those for curves **60** and **61**, because a larger change in total field with distance along the magnets occurs for curves **60** and **61** than for curve **58**. This would suggest that sharper reproduction pulses would result from the incorporation of the shunt, and that is indeed observed.

There is another interesting phenomenon suggested by this data. For example, the shape of curves **60** and **61** have an asymmetry which inverts with a

change in the direction of the bias current. Either the measured fields are low and flat across a region of magnetization, or the fields have high values and strongly curved character. A careful inspection of curve **60** suggests that the position of the center of the first transition from positive to negative magnetization occurs **after** (larger relative position) **58a**. Likewise, the position of the center of the second transition from positive to negative magnetization occurs somewhat **before** (smaller relative position) **58b**. For curve **61** the situation is just the reverse. The position of the center of the first transition from positive to negative magnetization occurs **before** position **58a**, while the position of the center of the second transition occurs **after** position **58b**. The measured positions of the transitions in the shunt material appear to be shifted with respect to the measured positions of the transitions with no shunt. This appears to be related to the magnetostatic interaction of the head bias field with the field from the magnets (recorded bits), since there was no relative motion between the head and the magnets when the measurements were made.

For the negative bias (curve **60**), the field from the head is in the same direction as the field in the shunt (created by the magnets) for the regions indicated as negative in Fig. **9b**. The head field is in the direction opposite to that in the shunt for the region indicated as positive. For the positive bias (curve **61**) the description is just the reverse. Where the head field and the field in the shunt from the magnets are in the same direction, the measured horizontal field strength is about 1000 gauss. The true field strength in the shunt would be on the order of 10,000 gauss for a reasonable conversion factor of 10. In that case the saturation level would be about one-half, but the shunt is below full saturation regardless of the exact conversion factor.

Where the field in the shunt from the head and from the magnets are in opposite directions (i.e. the positive region of curve **60** and the negative region of curve **61**) the measured field is low, about 100 gauss or less. However, its direction is opposite to the direction of the field in the shunt without the bias (curve **59**). Initially, it might appear that the change in field strength in the shunt across the transition is large (about 1000 to 100 gauss); however, the way the instrument makes the measurement must be taken into account. The magnet field sensor (Hall probe) has a finite area (width is about 0.1 inches). The probe measures the net difference in the fields from opposite directions that pass through the sensing area. When all

of the contributions to the field are in the same direction, the measured field is representative of the actual flux line density at the sensor. When the contributions to the field are equal but oppositely directed, the measured field could be zero, even though the field line density is high over a large part of the sensor area. In addition, the measurement geometry is such that the bias field from the head can take a low reluctance path around the top of the sensor aperture, while the opposite field from the magnet can take a low reluctance path around the bottom of the sensor aperture. Because of this geometrical effect, the fringe field in the sensor aperture could be lower than otherwise expected. A sensor that could measure the magnetic field strength essentially at a point and in a vanishing small aperture would be required to accurately map the spatial field distribution in this experimental setup when the fields oppose each other.

The scalar permeability of a magnetic material is determined by the magnitude of the field, not its direction. For the variable reluctance shunt of this invention, the **effective permeability** would be given by the appropriate integral of a set of differential elements, and their associated field strengths, over the volume of the shunt material effected by the field from the head bias and the recorded transition. The experiment described above gives some insight only into the field structure along the centerline of the head gap, not over the entire volume of shunt material influenced by the head bias field. However, based upon the experimental data and the considerations of the measurement techniques, it appears reasonable to conclude that the change in the **effective permeability** of the shunt across a transition is consistent with an effective change in field strength of a few hundred gauss.

A computer modeling program was developed and used to solve for the signal output from isolated pulses based upon the reluctance circuit in Fig. **8a** with the permeability changing in the gap shunt as depicted schematically in Fig. **8b**. Typical recording parameters for an ordinary thin-film inductive head and reasonable values for shunt properties were selected. The magnetomotive force in the head core was computed by using a DC bias current of 1mA and assuming 32 turns for the coil. The flying height of the head was 3 micro inches, and the recorded pulses were separated by 1750 nanoseconds (or 525 micro inches in distance), corresponding to a relative velocity of 7.5 meters per second between the head and media.

The change in magnetic field strength in the shunt was modeled as an arc tangent function with a transition width similar to what is often used to model a recorded transition, and consistent with the experimental results previously discussed. The change in magnetic field strength across a transition (used to compute the effective change in shunt permeability) was 400 gauss. Because of the low frequency of the isolated pulses, the reluctance of the gap shunt was assumed to be totally real (no imaginary part) for these calculations. The model output is shown in Fig. **9c**. The predicted signals have the expected character of isolated pulses and the signal strength (peak height) is in the typical range of a few hundred microvolts. This result suggests that the simplified model used to describe the effective change in the permeability of the shunt, is to first order, approximately correct.

It is noted that a similar result could have been obtained by modeling the reproduction pulse as an equivalent inductance change in the head electrical circuit instead of a reluctance change in the magnetic circuit. The output voltage signal from the head is produced by a change in the bias flux in the transducer core through its reluctive interaction with the recorded bit. The voltage induced in the head coil is proportional to the time rate of change of flux in the core and is given by $-N(d\varphi/dt)$ where N is the number of turns in the coil and φ is the flux in the core. The same pulse would be generated by computing the voltage for the appropriate change in the inductance and current in the electrical circuit of the head. The voltage is given by $d(LI)/dt$ where L is the inductance of the head circuit and I is the current in the circuit. The derivative results in two terms, $I(dL/dt)$ and $L(dI/dt)$. In many electrical circuit applications L is constant when the coil does not enclose permeable material (W. Trimble and V. Bush, "Principles of Electrical Engineering", Third Edition, John Wiley & Sons, Inc., 1947), so dL/dt would be zero. However, in the head circuit the coil encloses the permeable head core, so both terms must be computed. Since the calculation of L requires the calculation of the reluctance first, it seems more fundamental to simply calculate the pulses shapes straight from the reluctance model.

To physically demonstrate the operation of the variable reluctance gap shunt reproduction system, a magnetic recording medium was prepared which met the requirements previously described. In this example a single 380Å layer of CoCrPtTa served as recording layer **29** (in Fig. **1**). The coercivity was about 1800 Oersteds.

Magnetic exchange breaking layer **30** was about 100Å of carbon nitride. Permeable shunt layer **31** consisted of two laminations of Permalloy, each 200Å thick separated by 50Å of silicon. The top protective layer (not shown in Fig. **1**) was 100Å of silicon. Two commercially available transducers were used. One was an ordinary inductive thin-film head, and the other was a double MIG (metal-in-gap) inductive head. The thin-film head had a 44 turn coil, a gap length of 0.3 micrometers, and a 5 micrometer read track width. The MIG head had a 32 turn coil, a gap width of 0.3 micrometers, and a 7 micrometer read track width.

To illustrate operation in the DC bias mode, a DC bias current sufficient to cause operation in variable reluctance zone **36** was applied to the coil of a thin-film head during the read back of isolated transitions written to a magnetic recording medium having shunting layer(s) as previously described. Fig. **10a** shows the pulse shapes as seen on the oscilloscope during the playback of the recorded transitions. The results indicate that there is significant agreement between the pulse shapes predicted by the model (Fig. **9c**) and the pulse shapes seen in the actual experiment (Fig. **10a**). When the same head and electronics were used to read isolated pulses from a conventional recording medium without a shunt layer(s), but with an otherwise identical recording layer(s), the read back pulses shown in Fig. **10b** were obtained.

A comparison of Figs. **10a** and **10b** shows that the pulse heights obtained by this invention are greater by about 50 microvolts than the pulse heights obtained in conventional recording, even though the transducer is spaced further from the recorded transitions by the additional thickness of the shunting layer(s). The heights of pulses **62** and **63** in Fig. **10a** are not identical with each other, pulse **62** having greater amplitude than pulse **63**. The fundamental cause of this asymmetry seems to be related to the magnetostatic interactions discussed earlier in the large-scale experiments; however, other factors may be contributing as well. For instance the non-linear change of permeability with field strength, a magnetic offset in the shunt, or the effects of stress in the coating could contribute to asymmetries. If the direction of the DC bias is inverted, the relative heights of pulses **62** and **63** will also be inverted, at least approximately. In contrast, conventional recording pulses **64** and **65** in Fig. **10b** are substantially symmetrical in amplitude. Conventional PD (Peak Detection) recording channels that use 1,7 and other RLL codes can be degraded by

the inherent pulse height asymmetry regardless of its origin. However, it will be shown that this asymmetry is not detrimental to the reproduction system of the present invention.

The variable reluctance gap shunt reproduction system offers another significant advantage over conventional recording systems which use thin-film heads. In Fig. **10b** the features identified as **66** are known as head "undershoots". They are caused by magnetic interactions between the recorded transitions and the leading and trailing edges of the finite pole tips of a thin-film inductive head. The heights of the undershoots average approximately 7% of the main pulse peak height, and they cause degradation in channel performance by decreasing the signal to noise ratio. The advantage provided by the variable reluctance gap shunt system is to substantially eliminate these undershoots, as indicated by their absence in the corresponding positions in Fig. **10a**.

To further demonstrate the DC bias mode of signal reproduction, a set of experiments was performed using the recording medium and the MIG transducer previously described. Transitions in the form of di-bits were recorded at a frequency of 5 megahertz and at a relative velocity of about 8.9 meters per second between the medium and the transducer. The DC bias level and direction was monitored by a voltmeter across a 10k ohm resistor. Therefore, a bias current of +/- 1 milliampere would flow through the coil in the transducer for a bias voltage drop of +/- 10 volts across the resistor. In the following discussions the bias is referred to in terms of volts across the resistor for convenience. It is recognized that current is the more fundamental parameter.

Data in the form of read back pulse shapes were taken for a range of bias voltages. A digitizing storage oscilloscope was used to capture the pulse shapes. At each bias level the wave forms for both positive and negative bias directions were averaged to reduce noise, stored in separate channels, then displayed together and printed. It was discovered that the reproduction signal from a particular transition either leads or lags the position of the originally recorded transition by as much as 45° in phase, depending upon the level of the DC bias and its direction with respect to the recorded bit.

The effect is illustrated for the MIG head by comparison of two selected reproductions of the oscilloscope wave forms shown in Figs. **11a,** and **11b**. The

recorded transitions for reproduced pulses in the positive direction were initially written at times t_1; t_2, and t_3. Transitions for reproduced signals in the negative direction were written between these times. These are not isolated pulses as shown previously. They are a continuous sequence of di-bits which correspond more closely to the transition density of actual recorded data. In the figures the wave forms depicted by dashed lines, **67**, were reproduced using a negative DC bias voltage. solid lines. **68**, represent the results for positive bias. This nomenclature is applied consistently in both figures.

For Fig. **11a** the bias voltage was set at +/- 7 volts. The peaks reproduced with negative DC bias (**67**) have slightly lower amplitude than those read with positive DC bias (**68**). Further investigations of the heights of reproduction pulses as a function of bias voltage suggest that this pulse height asymmetry is an artifact caused by a magnetic offset in the media itself. The more important aspect of this data is in the phase shift between the signals. For negative bias (**67**) the signal peaks are **early** with respect to the original positions of the positive transitions by about 45° in phase, but the peaks are **late** with respect to the original positions of the negative transitions by the same amount. For positive bias (**68**) the signal peaks are **late** with respect to the original positions by about 45°, but the peaks are **early** with respect to the original positions of the negative transitions by about the same amount. With respect to each other, the negative and positive pulses of each signal are shifted by twice the amount, about 90° in phase. The results of the large-scale experiments previously described seemed to suggest that some type of phase shifts in the reproduction signals should be found.

This behavior of the read back signals demonstrates that dual states can exist for any recorded transition, depending upon the level and direction of the bias current and the direction of magnetization in the media when the transition is sensed. This suggests that two signals separated by 90° from each other can be generated from reading the same set of transitions with different bias current directions. The two states for positive bias and two states for negative bias make a total of <u>four</u> independent states which may be used in an appropriate data modulation and encode/decode scheme to represent additional symbols or pairs of binary digits (not just "1"'s and "0"'s separately) to record and retrieve data in a non-binary mode.

In Fig. **11b**. the bias voltage was set at +/- 14.2 volts, sufficient to saturate the shunt. At this bias level the pulse height asymmetry has essentially vanished along with the phase shift. The wave form is very similar to a conventional recording playback signal. At this level of DC bias the "virtual gap" as taught in '922 has been established, and the reproduction system is no longer functioning in the variable reluctance mode. The dual states for each transition no longer exist.

Figure **11c** shows a summary of the data for DC bias using a thin-film head and a medium that has a shunt consisting of two Permalloy layers each about 200Å thick. Two quantities are plotted against the bias voltage, the normalized peak to peak amplitude of the output signal, and the phase difference between the position of the reproduced signal and the original position of the recorded transition. Output signal **69** is slightly below its maximum value at the starting DC bias of -10 volts. rises to a maximum at -6 volts, and then drops smoothly to zero at +2.5 volts. As the bias increases to +10 volts and above, the output signal returns to its maximum value. Over the same range of bias voltage, phase **70** is zero at -10 volts (shunt is near saturation) and drops smoothly to -45° at -2.5 volts bias. Upon further increases in bias voltage the phase goes back through zero at +2.5 volts and increases to +45° at +7.5 volts. The phase then approaches zero again as the bias increases and drives the shunt toward saturation in the opposite direction.

The bias voltage at which shunt saturation occurs is different for this data and that shown previously in Fig. **11b** because of the different physical structure of the heads. The thin-film head used here has more turns on its coil and narrower pole tips than the MIG head used to reproduce the wave forms in Fig. **11b**. Therefore, for the same bias voltage more flux is produced in the shunt.

Output **69** and phase **70** are not symmetrical with respect to zero bias, but are offset by about 2.5 volts. Several factors could contribute to this effect including hysteresis in the shunt material, coating stress, and the alloy composition of the shunt. However, the most important cause could be the magnetic anisotropy produced by the conventional circumferential texture in the substrate. The starting bias of -10 volts essentially saturated the shunt in one direction. When the bias was reduced to zero, a residual field was left in the shunt which required a +2.5 volt bias to remove. If the shunt is initially saturated in the positive bias direction, the zero offset is in the opposite bias direction. Lowering the coercivity of the shunt, which

was previously described as desirable, would help to minimize the offset. It is anticipated that the use of conventional or alternate substrates with isotropic texture (i.e. not circumferential) or smooth (no texture) could also be effective. At higher bias voltages some erasure of the originally recorded transitions begins to be detectable. The exact level where erasure starts depends largely upon the coercivity of the recording layer in the medium, higher coercivity being more difficult to erase.

The experiment described by the data summarized in Fig. **11c** was repeated using the same thin-film head, but a different recording medium with a shunt, consisting of an equivalent (thicker) single layer of Permalloy. The summary of this data is given in Fig. **11d**. In both figures the signal level used to normalize the output was the same. The general nature of the changes in output **71** and phase **72** with changes in bias voltage is very similar to that for the laminated shunt layer shown in Fig. **11c**. In particular output **71** is practically the same as output **69**. Even the offset with respect to zero bias occurs at about the same point. Phase **72**, while similar in form to phase **70**, is different in its details. First, the points at which phase **72** passes through +/- 45° are not as sharp as the corresponding points for phase **70**. The implication being that the 45° phase positions are somewhat less well defined for the single layer shunt. Additionally, the difference in the bias voltage between the 45° phase points is much less for the single layer shunt than it is for the laminated dual layer shunt. For phase **72** (in Fig. **11d**) this difference is about 6 volts, while for phase **70** (in Fig. **11c**) the difference is about 10 volts. The output signal levels corresponding to the 45° phase points are higher for the laminated dual layer shunt than for the single layer shunt. These differences cannot be attributed solely to the difference in the shunt structure, because the textures were slightly different and the media were deposited in different coating machines.

A recording reproduction system using only DC bias and operating at the 45° phase points, should have somewhat better performance with the laminated dual layer shunt medium because of the increased signal levels corresponding to these positions. Because of this, media with a shunt consisting of multiple laminations is preferred over media with a single shunt layer, even though the single shunt layer media could still be used advantageously. In recording reproduction systems not designed to specifically take advantage of the 45° phase shift points, the media with a single layer shunt could perform as well as the media with a laminated shunt. The most

important aspect of this **variable reluctance** invention is that for either single or multiple layer shunts there exists a **phase vs output** or **phase vs gain** relationship which can be exploited to achieve an improved, but unconventional, recording reproduction system.

The above experiments were repeated using a data frequency of 10 megahertz instead of 5 megahertz. The results were that the phase vs output relationships were about the same as at 5 megahertz. This means that the magnitude of the actual timing difference was cut in half because the frequency was doubled. In conventional RLL codes used presently, the write and read pre compensation would have to be adjusted for constant phase shifts in the present invention rather than the usual constant timing shifts. At a higher level of bias when the shunt is saturated, the phase shift is substantially eliminated, and the conventional RLL codes could work normally without additional phase pre compensation. This saturated mode is the mode of operation anticipated by '922.

The most advantageous mode of operation uses an AC sense current (or AC with DC bias) instead of DC bias alone. It can best be described and specified by experimental results. The method of signal reproduction using an AC sense current is demonstrated using the magnetic disk medium with a laminated dual layer shunt and the MIG head that was previously described. The same recording of di-bit pulses at a frequency of 5 megahertz are now reproduced using an AC sense current. The bias frequency was set at 15 megahertz and held in synchronism with the data by using a phase lock loop. The AC sense voltage was connected to the transducer coil through the same 10k ohm resistor as was used for the DC bias case.

The basic use of an AC sense current is illustrated in Fig. **12a**. All of the pulse heights are at the same scale. Reproduction signal **73**, used here for reference, is the same as that given for DC bias in Fig. **11b**, but is shown at half the vertical scale. Signal **74** is the AC sense signal running at 3 times the frequency of the data signal, and at a peak to peak amplitude of about 0.3 millivolts. It was recorded with the magnetic medium at rest with respect to the transducer. In addition to the sine wave used here for illustration of an AC sense signal, many other forms of the AC sense signal, for example square or triangular waves, could be effectively used. Note that the peak to peak amplitude of the AC sense voltage is far below the typical DC bias of several volts. In fact, it is approximately the same level as recorded signal

73, which was reproduced with a 14 volt DC bias. For this reason the AC signal is called a sense signal instead of a bias.

When the magnetic medium is placed in motion with respect to the transducer and the AC sense current is phase-locked to be in synchronism with the data, reproduction signal **75** is obtained. The AC sense signal is seen to be significantly **modulated** by the recorded data even though the flux produced by the AC sense current in the coil of the transducer, and hence in the variable reluctance element, is much smaller than the flux produced by typical DC bias voltages. The same level of DC bias alone (i.e. 0.3 millivolts) would be far to small to be useful, even in the variable reluctance mode. If AC sense signal **74** is subtracted from reproduction signal **75**, final AC reproduced signal **76** is obtained. Signal **76** has about the same amplitude as DC reproduced signal **73**, but the peaks are sharper and better defined. If the signals were merely added together, the subtraction of AC sense signal **74** from AC reproduced signal **75** would have resulted in the replication of DC reproduced signal **73**, instead of signal **76**.

The AC case is a significant improvement over the DC case because the signal to noise ratio has been improved. Additionally, the phase shifts previously described with respect to DC bias, are also observed with AC sense signals. With proper adjustment of the bias frequency, any particular recorded transition can be sensed with either +45° or -45° phase shift. The Fourier transform (power spectrum) of the reproduced signals reveals that the AC sense reproduced signal has more power than the DC bias reproduced signal in its higher frequency harmonics. In fact the AC case has spectral energy beyond the gap null (where two recorded bit lengths are equal to the gap length), while the DC case has none. This implies that intelligent information can be derived from track recording densities far above that possible with conventional recording. For the variable reluctance technology, there is no classical physical gap length (and gap null) that can be associated with the nature of the reproduced signals as there is with conventional and '922 recording.

In the above example (Fig. **12a**), an AC sense current alone was used for reproduction signal **75**. However, if the shunt layer were somewhat thicker than the optimum as previously discussed, a small additional DC bias along with the small AC sense current would serve to adjust the operating point for the variable reluctance shunt to its optimum range. It is quite apparent that so small an AC sense current

cannot result in saturation of the shunt as can happen for large DC bias. In the case discussed here, the peak to peak voltage amplitude of the AC sense signal is much smaller than the 14 volt DC bias. applied across the same resistor, by a factor of more than 46,000. The change in permeability caused by the written transition modulates the AC sense current. but the AC sense current is too small to cause significant modulation of the permeability. The absolute value of the permeability should be smaller at higher frequencies. and the slope of permeability vs field strength could be higher. but a change by so large a factor as 46,000 was unexpected.

It is possible that the imaginary component μ'' could be non-zero at these frequencies for thin layers of the material; however, this would not be expected for the bulk material based on available data. In the case that μ'' were non-zero. the reluctance of the shunt would be a complex quantity, analogous to complex impedance in electrical circuits. It is also possible that the small AC sense current results in a boost to the speed at which the permeability is varied as the transducer passes a recorded transition. The region of the gap shunt that is slightly magnetized by the small AC sense current could first be attracted to the approaching transition, and then switched just at the transition to be repulsed away from it. Although the change in reluctance would be small, the change in switching time would be correspondingly smaller, still leading to a relative large rate of change of the bias flux by the recorded transition. In either or both of the above scenarios the generation of the observed higher harmonics might be expected.

When the frequency of the AC sense signal is much higher than the frequency of the recorded transitions, the reproduced wave form shows the AC sense signal with clear envelope modulation due to the recorded transitions. An example of this behavior is illustrated in Fig. **12b** for isolated pulses. Wave form **77** is a 20 megahertz AC sense signal with no relative motion between the head and the medium. The peak to peak amplitude of the bias is about 300 millivolts as in the previous example The recorded data was at a frequency of 1 megahertz to give essentially isolated pulses. Curve **78** is the resulting signal with relative motion between the transducer and the medium. The AC sense voltage is seen to be modulated by the underlying transitions. In this example the AC sense signal was not synchronous with the frequency of the recorded data as it was in the previous

example. However, the extra constraint of synchronism with the data frequency, or a higher multiple harmonic of the data frequency, can be used to advantage in a data encode/decode scheme using M-ary techniques.

If the **peak to peak amplitude** of the AC sense signal is increased, the output voltage increases in amplitude until the preamplifier becomes saturated. However, the modulation on the output voltage (the actual reproduction signal) is of the same order of magnitude as that observed when an optimum DC bias alone is used. The significance of the AC mode is that the signal to noise ratio has been increased over both conventional recording and the DC bias mode of this invention. This allows recording density to be increased using components which are currently available, because in AC mode, the ordinary thin film head can have improved sensitivity that is equal to or greater than that of an MR head.

There are magnetic circuits used for magnetometers which in principle might be related to the variable reluctance magnetic circuit of this invention. In a recent review paper, P. Ripka (Sensors and Actuators, **A 33** (1992), pps 129-141) summarizes the history and advances made in fluxgate sensors, sometimes referred to as second harmonic magnetic modulators. These sensors are used to detect weak DC and low frequency AC magnetic fields. The basic sensor consists of a rod or torus shaped core of magnetically permeable material with two coils, one for excitation of the core and one for signal pick-up. An AC current placed on the excitation coil is of sufficient magnitude to drive the permeable core into saturation each half cycle of the AC current. A weak magnetic field in the vicinity of the permeable core can be detected on the pick-up coil as the second harmonic of the AC exciting field.

The devices have been in use since the early 1900's, and have been incorporated in devices for detecting submarines, for geophysical prospecting, and for mapping planetary and space magnetic fields from satellites. They are large devices when compared to the size of a recording transducer, and apparently they have not found an application in the magnetic recording industry.

The variable reluctance circuit of this invention differs from the classical fluxgate sensor circuit in several ways. The recording transducer has only one coil with typically 20 to 50 turns while the fluxgate has two coils and about 2000 turns. In the fluxgate the core is alternately saturated, while in the recording transducer of

this invention the AC sense signal is so small the field level in the core is near zero and hardly changes. AC currents of sufficient amplitude to saturate the transducer core would be far greater than that necessary to erase the recorded data. However, the flux variation in the variable reluctor (part of the transducer core magnetic circuit) does experience a larger field oscillation due to the AC sense signal because the AC flux from the bias is more concentrated by the smaller cross sectional area.

With reference to Fig. **2**, in the fluxgate the permeability of the core is varied from region **37** through regions **36** and **35** to zero field and back to region **37** during the AC cycle. In the variable reluctance AC mode the variation in permeability of element **34** (in Fig. **1**) is much less than that illustrated for DC bias in region **36** of Fig. **8b**. However, Ripka (1992) in his derivation from Faraday's Law of the induce voltage in a fluxgate sensor refers to the term containing $d\mu/dt$ as "the basic fluxgate equation". In this invention the variable reluctance is caused by a similar $d\mu/dt$ effect. While there are many differences in form and circuit application, the basic physics have similarities. Variable reluctance in the AC mode could alternately be characterized as a "fluxgate-like" method for sensing the magnetic field from the recorded transition. The variation in the permeability of the sensor element is varied over a much smaller range, and saturation is avoided. The AC sense signal is modulated at the data frequency and contains higher order harmonics somewhat analogous to the fluxgate sensor.

If the **frequency** of the AC sense signal is increased, a point will be reached (depending upon electrical components and physical dimensions) when the head circuit will go into resonance. For conventional head circuits, the region of resonance has low Q and does not lead to large increases in signal amplitude caused by the perturbing recorded transition. A head circuit could be redesigned to provide a high Q resonant circuit for increased signal amplitude when used with this variable reluctance technology. The change of magnetization across a transition will cause a change in reluctance and a corresponding change in inductance in the head circuit. This change in inductance will cause a large change in the amplitude of the AC sense signal which is the detection of the transition. Since a high Q circuit has relatively narrow bandwidth, care must be taken to insure that the data rate is less than the Nyquist limitations imposed by the frequency of the AC sense signal and the Q of the circuit.

At even higher frequencies the variable reluctance shunt could go into resonance. This condition is related to the fact that the impedance of the shunt becomes a complex quantity, and μ'' attains its maximum value at the resonant frequency. Thus, it should be possible to operate the reluctance circuit (Fig. 8a) as a tuned oscillator or tank circuit similar to that previously described for the head circuit. In this mode of AC operation, the perturbation of the circuit by a recorded transition would produce a higher amplitude reproduction signal than the non-resonant AC or DC modes previously described. The materials and conditions necessary to sustain this resonant mode must be carefully chosen and properly optimized, as those skilled in the art will recognize. The higher amplitude might not be accompanied by improved signal to noise ratio because the bandwidth of high Q tuned circuits is relatively narrow. Since the tuned circuit acts as an amplifier (modulator), disk noise could be amplified along with the signal. If this were the case, the overall system signal to noise ratio could still be improved by amplifying the signal until the noise from the head and channel is smaller than the noise from the media. Although this reluctance circuit resonant mode would be a very attractive mode of operation for this invention, its implementation will have to be delayed until heads are developed that have high enough frequency response to make it possible. Experimental heads that have laminated cores and pole structures appear to be candidates for implementation of this resonant frequency mode.

It is worthwhile to consider the use of this new recording reproduction system with modulation schemes that are not used (and cannot be used) in conventional recording. For instance, in conventional recording there is no intelligent information contained in the magnetic direction of the recorded transition - they must always alternate. However, in the present invention an extra recording symbol can be obtained with synchronous AC sensing. Just as in conventional recording, the written transitions must always alternate in magnetic direction, but in this new system any particular transition can be slightly advanced or delayed in time so that it is written in the direction of the synchronous AC sense current or in opposition to it. Therefore, the data modulation scheme could consist of no transition written for a zero, a transition in the direction of the AC sense signal for a one, and a transition in the opposite direction of the AC sense signal for a two. The binary schemes used in conventional recording use only a "0" or a "1", but the scheme just described, and

enabled by this invention; would use a "0", a "1", and a "2" to record and reproduce digital data. It would be a ternary system rather than a binary system.

As another example, consider the Phase Shift Keying (PSK) type of data modulation that is commonly used in wireless communication systems. Schematic representations and explanations of several systems are given by W. Tomasi ("Advanced Electronic Communications Systems", Second Edition, Chapt. 1, Prentice Hall, 1991). These systems modulate a carrier frequency with sets of binary data and encode and decode them in phase. In one common implementation called Quaternary PSK there are four symbols that represent the numbers 0,1,2, and 3 (i.e. 00, 01, 10, and 11 in binary representation). The interesting aspect of this modulation system is that there are two channels (I and Q) which are mixed together but are always 90° apart. In the normal use of this modulation scheme for communications, the data in the Q channel is rotated 90° from the I channel and then mixed with it before transmission to a receiver. With this new recording reproduction invention the mixed I and Q channels can be recorded, and then later retrieved because a 90° phase shift function is incorporated into the interaction between the transducer and recording medium. This has **never been possible before** because **no conventional recording system** has ever been able to store signals that have a 90° phase relationship to each other, and then demodulate those signals without losing the phase relationship. Because of the bias vs phase and output relationships (Fig. **11c**) any PSK system is possible; but the QPSK system has better output levels than other systems that have more phase relationships.

An example of a PSK communications system that has been modified to permit timing delays in transmission and reception due to the incorporation of this invention is shown in Fig. **13**. The PSK communication system as indicated by **79** would normally consist of an encoder/decoder **206** connected by a line **208** to transceiver **207** for linkage to antenna **209**. In the modified system signal connecting means **208** is removed and a variable reluctance phase recording and reproduction system **210** is inserted between **206** and **207** and signals are routed by means **211** and **212**. The variable reluctance recording and reproduction system **210** is able to record data that is encoded in phase, and delay the transmission by some arbitrary amount of time. The timing can be adjusted to be short (order of a millisecond) by using two heads running in tandem, or could be arbitrarily longer using either single or

multiple head arrangements. A delay in reception is affected by the inverse process. QPSK would be the optimum communication system for use with the variable reluctance phase recording technology because the signal strengths are higher for the 90° case.

The above examples of the use of this new recording reproduction system with non-conventional data modulation schemes illustrate two of many possible approaches to implementation. It will be appreciated by those skilled in art that there are a large number of data modulation schemes both already existing and that could be devised which could advantageously use the linear phase vs gain attributes of this new recording reproduction system to provide higher density recording and/or increased data rates.

In one alternative embodiment of the invention with longitudinal recording media, the shunt or variable reluctance layer(s) is placed across the pole tips of the transducer instead of on the media. The layer(s) functions with AC and/or DC bias in the same way that it does in the previously described preferred embodiment. In practice, the gap bridging shunt could be formed by depositing the shunt material onto a finished head by some commonly used thin-film deposition technique. Ideally the shunt should, in this case, be in intimate atom to atom contact with the head core material at the pole tips. However, in practice this may not be an easy task if use is made of already finished heads whose pole tips may have become contaminated in subsequent handling. In this case the existence of any magnetic exchange breaking region between the poles and the shunt should be minimized to the extent possible consistent with economical manufacturing procedures. If this principle is followed, the added reluctance caused by the contaminated region should not seriously degrade the reproduction signal. As in the preferred embodiment, the shunt could be made from a single layer or laminations of two or more layers.

This embodiment has some characteristics which are similar to some previous art for magnetically soft materials used in heads; however, as with the preferred embodiment on the disk, the operation is completely different. U.S. Patent 3,432,837 ('837) issued 11 Mar 1969 teaches a magnetic head with magnetic material as a gap bridge. The material bridging the gap is specified to have a permeability less than that of the head core. This was to insure that some of the flux from the recorded transition flowed into the head core. No bias was used on the head to vary the

permeability of the material bridging the gap. In the present invention the permeability should be as high as possible and **higher** than the permeability of the head core would be preferable.

U.S. Patent 5,105,323 ('323) issued 14 April 1992 was an improvement on '837. It taught a gap bridging magnetic material with the magnetic anisotropy axis aligned in such a way as to further reduce the permeability of the material in a direction parallel to the direction of information travel. Both patents attained a lower permeability by material composition selection and orientation, and the lower permeability material covered the entire area of the head poles. In this invention the permeability is high over the entire region of the poles, but varied in the region of the gap by a bias current that does not cause saturation of the material.

An Ampex embodiment, U.S. Patent 5,130,876 ('867) differs from both '837 and '323. In '867 gap bridging magnetic material has cross bias magnetic fields applied to it in a manner which causes saturation in all regions of the permeable material along the gap except where the bias fields cross. By varying the bias fields the unsaturated signal transfer zone is made to scan along the length of the head gap, but in the direction of the recorded bits. In this embodiment the magnetic media is not in relative motion with respect to the head. The necessary motion to cause an induced signal is provided by the scanning speed of the saturation region in the magnetic gap bridge.

In summary, the gap bridge in this invention differs from '837 and '323 in that the permeability of the magnetic material is high over the entire surface of the head pole tips, and a bias is used to vary the permeability only in the region of the gap. It differs from '867 in that the bridge material is not saturated anywhere, the unsaturated zone is not scanned along the gap, and the media is in relative motion with respect to the head.

Fig. **14** illustrates schematically this alternate embodiment. The numerals indicate elements that are common to those identified with the same numerals in Fig. **1**. Layer **31** in Fig. **1** does not exist in this alternate embodiment as an extensive member covering the recording medium. Only the elements **33a**, **34** and **33b**, which are now placed across the pole tips of transducer **20**, are necessary. As previously discussed, the contact between elements **26a** and **33a** and between elements **26b** and **33b** should be as intimate (atom to atom) as possible. The recording media for this

embodiment is the same as that used for conventional recording. Therefore, layer **30** in Fig. **1** is no longer needed. The recording medium for this embodiment is represented by **29**, and the other conventionally used layers (as discussed earlier for Fig. 1) are omitted for clarity.

The flux generated by a current in coil **23** now flows through element **25**, which is an air gap, and through variable reluctance element **34**, which presents a lower reluctance path. The application of AC and/or DC bias has the same functionality as previously described. However, the flux from the recorded transition which modulates the reluctance in element **34** is now weaker because of the increased distance **27** (the flying height). Although this is a disadvantage for this embodiment, at low flying heights the signal strengths are sufficient to make it a useful alternative implementation.

There is an advantage to this embodiment which is realized in the writing mode. Because the high write current causes complete saturation of element **34**, there is no increased write spacing loss over that of conventional recording technology. This occurs because elements **33a** and **33b** then become mere extensions of the pole tips of the head. Also, this alternative embodiment becomes indistinguishable in principle from the first embodiment when flying height **27** approaches zero.

Another alternative embodiment for use with longitudinal recording media is shown schematically in Fig. **15**. In principle it functions substantially similar to the previous embodiment shown in Fig **14**. However, it differs in the way the variable shunt is made. Here the concept is to build the variable shunt element **34** into the gap of the head as a process step during the manufacture of the head. Intimate atom to atom contact between element **34** and elements **26a** and **26b** are more critical to this embodiment than the previous embodiment because the reluctance at the contact areas could be large due to the small cross-sectional area. Therefore, the areas of concern have been explicitly indicated in Fig. **15** as regions **80a** and **80b**. If these regions cannot be eliminated in manufacture, not only will the higher reluctance in these areas contribute to a reduced signal, but the "gaps" will act like secondary head gaps in conventional recording and produce spurious signals which will be detrimental in signal processing. This is in contrast to the previous embodiment in which a continuous layer covers the pole tips eliminating the possibility of spurious

gaps. Note that element **34** is indicated as not completely filling (vertically) gap region **25**. While an exact thickness need not be specified, it should be appreciated that the thicker the layer, the higher the bias current which will be needed to bring the variable reluctance operating point to the proper place on the permeability curve (zone **36**). Therefore, the thickness should be substantially similar to that of the two previous embodiments.

A hybrid embodiment could easily be formed by placing a portion of the variable reluctance shunt on the disk and a portion on the head. This would result in some compromise between the advantages and disadvantages of each embodiment. In such a hybrid embodiment the bias on the head might not be able to simultaneously adjust both shunt regions to the proper variable reluctance zone of the permeability curve. However, the part of the shunt that is positioned on the media could be adjusted in thickness so that the flux from the recorded bits will place the permeability in the proper zone without the help from the bias on the head.

A preferred embodiment for the use of this invention with perpendicular media is shown schematically in Fig. **16**. The embodiment includes a monopole transducer **82** and perpendicular medium **83**. Transducer **82**, as represented schematically, consists of a core with monopole head region **84** and flux return region **85**. Coil **86** threads a region of the core connecting regions **84** and **85**. Coil **87** loops around a lead to coil **86** to provide a means of applying an AC bias to coil **86** in similar fashion to that described previously in the longitudinal case. Magnetic flux created by a bias current in coil **86** will follow magnetic circuit path **88** in a direction depending upon the direction of the bias current. The tip of monopole region **84** is separated from medium **83** by flying height distance **89**. Flux return region **85** does not contact medium **83**, but it need not be separated from it by exactly distance **89**.

Perpendicular magnetic medium **83** consists of high coercivity recording layer(s) **90** with shunting layers **91** and **92**. The properties and function of shunting layer(s) **91** and its exchange breaking layer **93a** were previously described for both longitudinal and perpendicular media. Shunting layer(s) **92** and exchange breaking layer **93b** may be identical to layer(s) **91** and **93a**, or they may be similar to those described by Sugita (1987). Shunting layer(s) **91** contains variable reluctance element **91a** located directly below and approximately in line with monopole region

84. Regions of perpendicular magnetization in recording layer(s) **90** are indicated by arrows labeled **94**.

Reproduction of the recorded signal for this perpendicular embodiment is analogous and similar to that previously described for the longitudinal case. A non saturating DC bias current applied to coil **86** during reproduction establishes region **91a** as a variable reluctance element in magnetic flux path **88**. The permeability, and therefore the reluctance, of **91a** is varied by the alternate magnetization in recording layer(s) **90** as it moves relative to transducer <u>82</u>. The variation in the reluctance of element **91a** causes a variation in the bias flux created by the DC current in coil **86**, thus inducing an output voltage signal. If a low level AC sense signal or a combination of AC and DC is used for reproduction, the AC signal is modulated by the recorded transitions in similar fashion to that described for the longitudinal example.

The way DC bias is implemented in any of the embodiments is straight forward, a voltage is simply applied to the leads of the head through a resistor. However, for high frequency AC sense signal implementation, the AC response of the head itself can become a complicating factor. Placing the AC sense source directly into the head circuit through a resistor, as was previously done for demonstration at low frequencies, could cause undesirable effects at higher frequencies. A simple and functionally superior way to apply the AC sense signal was discovered. A single turn or two of wire is placed around one of the leads to the head, and the AC signal is fed into the wire. This induces the AC sense current into the head circuit in an easily controllable and non interfering manner. This procedure is illustrated in Fig. **16** by wire **87** which loops around a lead of coil **86**.

Fig. **17** shows schematically a block diagram of a signal processing system **95** that uses a magnetic recording medium **96** in the form of a rigid disk as an example. Those skilled in the art will appreciate that the apparatus and method of the present invention may be adapted to other forms of magnetic recording media, such as tape or cards. Disk **96** may contain either a longitudinal or a perpendicular recording layer(s) with an exchange broken shunt layer(s) as previously described. Disk **96** is mounted on motor spindle **97** for rotation beneath magnetic transducer **98** that is threaded by winding **99** which carries current during record and playback operations. Winding **99** is used to carry input signal currents during record operation

modes, and bias and reproduction signal currents during playback operation modes. As described herein, bias signal currents for playback are relatively weak with respect to record currents and may be included with the record current as an optional mode.

In record operation switch **100** is open (or closed as an option) and switch **101** is in its first position as indicated by the solid line. Signal current from data encode source **102** is amplified by record driver **103** and transmitted through switch **101** and line **104** to winding **99**. This signal current generates a signal flux in transducer **98** that fringes from the physical gap of transducer **98**, permeates the magnetic recording layer(s) of disk **96**, and is recorded therein. The magnitude of the signal current is adjusted so that the fringing flux from the physical gap is sufficient to saturate the shunt layer(s) on disk **96** in the region below the physical gap. The saturation enables the transfer of the record signal from transducer **98** to disk medium **96**.

In reproduction mode, switch **100** is closed and switch **101** is in its second position indicated by the dashed line. The closing of switch **100** couples an adjustable DC current source **105** through resistor **106** and an inductively controlled oscillator **107** through capacitor **108** to line **104**. Source **105** provides an adjustable DC bias current that is transmitted through line **104** to winding **99**. The DC bias current generates a DC bias flux that fringes from the physical gap of the transducer to permeate the shunt layer(s) of disk **96**. The DC bias current is adjusted to **partially saturate** the region of the shunt layer(s) proximate the transducer physical gap to form an optimum variable reluctance element **109**. Variable reluctance element **109** corresponds to element **34** in Figs **1**, **14**, and **15**, and element **91a** in Fig **16**. Operation within the optimum variable reluctance zone of element **109** enables flux from the recorded transitions on disk **96** to modulate the permeability of element **109** along the region of the permeability curve of the shunt layer(s) that is essentially linear.

The inductive reactance (X_L) in the electrical circuit of transducer **98** changes in proportion to the change in the permeability of variable reluctance element **109**, and the change in permeability is proportional to the change in the flux from the recorded transitions. This variable inductive reactance is indicated in Fig. **17** as an arrow labeled **110** on coil **99**. When the reproduction system is operated within the

boundaries of the variable reluctance zone of element **109** as taught in this invention. the relationship between X_L and the changing flux from the recorded transitions is monotonic and essentially linear. This is because of the near linear relationship between the change in permeability and the change in flux from the recorded transitions that occurs when the operation point of the system is located on the partially saturated linear slope of the permeability curve of the magnetically permeable material used to form the shunt layer(s). Those skilled in the art will recognize that there are numerous reproduction methods that can be devised which will take advantage of this near linear relationship between the flux from the recorded transition on disk **96** and the X_L (**110**) of the transducer circuit.

An example of one such reproduction method is to amplitude modulate an oscillator using inductive reactance **110**. An AC signal from oscillator **107** is fed into reproduction head coil **99** through capacitor **108** and line **104**. The value of capacitor **108** is chosen in conjunction with the change in X_L in the head circuit to give maximum modulation of the oscillator signal on line **104**. The amplitude of the signal from oscillator **107** should be sufficiently large to improve the overall system signal to noise ratio, but not so large as to create non linear modulation products or cause saturation of variable reluctance shunt element **109**.

The amplitude modulated signal on line **104** is fed into demodulator **112** through switch **101** and DC blocking capacitor **111**. The demodulated signal waveform will be proportional to the magnetization levels from the recorded data on disk **96**. The demodulated signal is then fed into data decoder **114** for restoration of the original recorded data.

Another reproduction technique could be linear frequency modulation (FM) or phase modulation (PM) of oscillator **107**. In this example the change in X_L in the head circuit caused by the variable reluctance of element **109** is used to frequency modulate the resonant tank circuit of oscillator **107** or to reactively phase modulate oscillator **107**. For either the FM or the PM example, the modulated signal from oscillator **107** is fed by line **115** through switch **101** into demodulator **112**. The frequency or phase deviation limits of oscillator **107** should be optimized with respect to the nominal center frequency of oscillator **107** as those with normal skill in the art will appreciate.

Demodulator **112** may be used in conjunction with phase lock loop **113** to reduce long term errors that may be created by variations in the rotational speed of spindle **97** or frequency variations or offsets of oscillator **107**. Additionally, the speed of motor **117** can be controlled by servo electronics **116**. The demodulated signal from **112** is then fed to data decoder **114** whose output is the original input data.

Alternatively, as suggested relative to Fig. 13 above, additional read/write transducers **98′** could also be used to accomplish delay in transmission of data through the medium **96**.

As previously suggested, the utility of the present invention depends, in practice if not in principle, upon the composition and structure of the materials selected for the shunt. It is important that the permeability changes rapidly with field strength at the operating point in zone **36** (Fig. 2), particularly when only DC bias is used. There is an analogy here with the MR head which seeks to have materials and conditions that result in large changes in **resistance** for a given change in magnetic field strength and direction. This variable reluctance technology seeks materials and conditions that result in large changes in **reluctance** through changes in permeability for a given change in magnetic field strength. For AC signals, the frequencies are high, and the DC and the low frequency permeability data that is available for some materials may not be useful as a guide in selecting those materials which will perform well.

The permeability of a magnetically soft material is usually different for different directions of the induction field with respect to the easy axis of magnetization in the material. The standard disk substrate used in the industry today is made from Nickel Phosphorus plated aluminum and is mechanically textured to develop substantially circumferential grooves on its surface. When this substrate is used for the practice of this invention, the grooves provide a mechanism for shape anisotropy which forces the shunt layer to have its easy axis of magnetization in the circumferential direction on the substrate. For many materials it may be more desirable to have the easy axis of magnetization in the radial direction or in some intermediate direction. A unique method of control of the easy axis of magnetization of the shunt material becomes possible if the circumferential texture on the substrate is eliminated. The substrate could be a non-textured standard substrate or an

alternate substrate material with a polished surface or a surface with isotropic texture of microscopic size.

A method commonly used for controlling the easy axis direction of a magnetically soft material on a substrate that has no preferred texture direction is to deposit the material in the presence of a magnetic field. This field must lie in the direction of the desired orientation and it must be large enough to saturate the shunt material. Alternatively, the material can be first deposited and then annealed in the presence of a magnetic field. This method causes a reorientation of the microcrystalline structure of the material to its easy axis direction. With this method of easy axis control, external magnetic configurations must be developed to provide the desired orientation. Often this is a complex and expensive process.

A simplified method that allows wide flexibility in the selection of the orientation direction of the easy axis is made possible by the disk structure used with this invention when the circumferential texture is eliminated. In this method the disk is manufactured using the art as commonly practiced in the industry. After deposition of the layers, the desired pattern of easy axis orientation of the shunt layer(s) is written into the underlying high coercivity recording layer(s). The shunt material is then subjected to a rapid thermal annealing, by flash lamps or other commonly used processes, which causes the easy axis of the shunt layer(s) to orient to the magnetic pattern written into the recording layer(s). The temperature of the disk during the annealing cycle remains below the Curie temperature of the recording layer(s) so the magnetic pattern is stable. After cooling down from the annealing cycle, the magnetic pattern on the disk is erased or overwritten with data during its use in the preferred embodiment of this invention. The orientation of the easy axis of the shunt material remains locked in the direction or directions imposed by the pattern written into the recording layer(s) during the annealing cycle. By this method the recording performance of the disk used in this invention can be easily optimized.

For embodiments in which the shunt is placed on the transducer, tradeoffs may have to be made between the magnetic properties of the shunt material and the properties of the material with respect to wear, tribology, and corrosion resistance. In consideration of the above, the most attractive material for the shunt would be one which is highly permeable, displays rapid change in permeability with field strength, is wear resistant, and has a composition that would withstand corrosion in typical

recording system environments. The materials known commercially as Alfesil (also sold under the trade name Sendust™), Super-Sendust, and various forms of iron nitride provide a reasonable match to the desirable properties.

In the preferred embodiment for both longitudinal and perpendicular media, the shunt layer is placed over the recording medium, but it is protected from head contact by a hard top overcoat layer. For this case the shunt material may not need to be as hard or corrosion resistant as might be desired for the alternate embodiments. Various varieties of nickel-iron alloys known commercially as permalloys, several high saturation alloys of cobalt-zirconium, and iron nitrides which are being investigated for use in transducers, could, among other magnetically soft materials, be useful. Iron nitride, iron tantalum nitride, and other iron nitrides are materials which are hard, corrosion resistant, and have extremely high levels of magnetic saturation. These materials would provide effective shunting in the form of very thin layers. Since the shunting layers can be thin, the larger write spacing loss that is a disadvantage in the preferred embodiment would be minimized.

For the case of high frequency AC signals, the permeability of the shunt material at the AC frequency is an important parameter for its utility. However, few investigations of materials at high frequency have been made, and even fewer published. The response of a shunt material in this recording reproduction system is in fact a test of the utility of its high frequency properties. In general the frequency response of magnetically permeable materials improves for thin laminations. It is therefore anticipated that, with AC sense currents, this recording reproduction system will have improved function if the variable reluctance shunt consists of multiple laminations of very thin layers of material.

While the invention has been shown and described with respect to particular references to various embodiments thereof, it will be understood by those skilled in the art that variations and modifications in form and detail may be made without departing from the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

CLAIMS

1. A variable reluctance magnetic recording/reproduction apparatus, comprising:

a magnetic recording medium having at least one layer of magnetic material for receiving and storing magnetic signals;

a magnetic transducer including a permeable core with its gap positioned relative to the surface of said magnetic recording medium for transferring signals with respect to said recording medium;

means forming at least one layer of a permeable shunt material between said permeable core and said magnetic recording medium;

means for moving said magnetic recording medium and said magnetic transducer with respect to each other;

means for generating a sense field in said core which partially saturates the region of said permeable shunt material bridging said gap during signal transfers from the magnetic recording medium to the magnetic transducer; and

means for generating a write field in the magnetic transducer which completely saturates the portion of said shunt material bridging said gap during signal transfers from the transducer to the recording medium, whereby data stored in said medium may be encoded and recovered in binary or non-binary form.

2. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 1 wherein said layer of magnetic material is formed on a substrate and has a layer of non-magnetic material covering it, and wherein said layer of permeable shunt material is formed over said layer of non-magnetic material.

3. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 1 wherein said magnetic recording medium includes a plurality of layers of magnetic material.

4. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 1 wherein multiple layers of permeable shunt material are disposed between said permeable core and said magnetic recording medium.

5. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 1 wherein said layer of permeable shunt material is carried by said core and bridges said gap.

6. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 1 wherein said layer of magnetic material has a coercivity of at least 1000 oersteds and said layer of shunt material has a coercivity of less than 200 oersteds.

7. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 1 wherein said transducer has an inductive reactance that changes in proportion to the permeability of a variable reluctance element formed by the portion of said layer of permeable shunt material bridging the gap of said transducer, and wherein said means for generating a sense field in said transducer includes

first means for applying a DC-bias current to said coil to cause partial saturation of said variable reluctance element,

second means for generating an alternating current for addition to the DC-bias current applied to said coil, and

third means for monitoring changes in the inductive reactance of said transducer caused by data stored in said second layer.

8. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 7 wherein said second means includes an oscillator, the output of which is frequency-modulated by data stored in said second layer, and said third means includes a demodulator for demodulating the modulated output.

9. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 7 wherein said second means includes an oscillator, the output of which is phase-modulated by data stored in said second layer, and said third means includes a demodulator for demodulating said modulated output.

10. A variable reluctance magnetic recording/reproduction apparatus, comprising:

a magnetic recording medium having at least a first layer of a highly coercive magnetic material for receiving and storing signals, and at least a second layer of a

magnetically permeable shunt material, said first and second layers being separated by an exchange-breaking layer;

a magnetic transducer having a magnetically permeable core with a transducing gap, said transducer being positioned relative to a surface of said recording medium for transferring signals through said second layer for storage in said first layer, and for subsequently reading out signals stored in said first layer;

means for moving said recording medium and said transducer with respect to each other;

means for generating a sense field in said transducer which partially saturates a region of said shunt material disposed directly below said gap during signal transfers from said recording medium to said transducer; and

means for generating a write field in said transducer which completely saturates a region of said shunt material disposed directly below said gap during signal transfers from said transducer to said recording medium, whereby data stored in said medium may be encoded and recovered in either binary or non-binary form.

11. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein the signals are stored in said first layer with their axes of magnetization substantially parallel to the plane of the recording medium.

12. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein the signals are stored in said first layer with their axes of magnetization substantially perpendicular to the plane of the recording medium.

13. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein said magnetic recording medium includes a planar substrate and wherein said first layer, said exchange-breaking layer and said second layer are formed on a surface of said substrate.

14. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 13 wherein the surface of said planar substrate on which said first layer, said exchange-breaking layer, and said second layer are formed has an isotropic texture.

15. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein said magnetic recording medium includes a plurality of layers of magnetic material having a coercivity of at least 1000 oersteds.

16. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein said magnetic recording medium includes a plurality of layers of shunt material having a coercivity of less than 200 oersteds.

17. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 16 wherein said magnetic recording medium includes a plurality of layers of magnetic material having a coercivity of at least 1000 oersteds.

18. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein said first layer, said exchange-breaking layer and said second layer are formed in a surface of a planar substrate.

19. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 17 wherein no permeable shunt layer substantially interacts with any magnetic recording layer through intimate atom-to-atom magnetic exchange coupling.

20. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein said exchange-breaking layer is formed by a relatively thin layer of non-magnetic material.

21. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein the materials and relative thicknesses of said permeable shunt layer and each said magnetic recording layer are such that flux from recorded transitions in said magnetic recording layer is substantially shunted by said permeable shunt layer.

22. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein the flux required to partially saturate a region of said shunt

material to its optimum operating point is less than the flux required to erase magnetic signals stored in the magnetic material.

23. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein the means for generating a sense field in said transducer includes an electrically conducting coil wrapped about a portion of said core.

24. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein said magnetic recording medium is included in a fixed or removable magnetic disk.

25. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein said magnetic recording medium is included in a magnetic tape.

26. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein said magnetic recording medium is included in a magnetic card.

27. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 10 wherein said transducer has an inductive reactance that changes in proportion to the permeability of a variable reluctance element formed by the portion of said layer of permeable shunt material bridging the gap of said transducer, and wherein said means for generating a sense field in said transducer includes

first means for applying a DC-bias current to said coil to cause partial saturation of said variable reluctance element,

second means for generating an alternating current for addition to the DC-bias current applied to said coil, and

third means for monitoring changes in the inductive reactance of said transducer caused by data stored in said second layer.

28. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 27 wherein said second means includes an oscillator, the output of which is frequency-modulated by data stored in said second layer, and said third means includes a demodulator for demodulating said modulated output.

29. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 27 wherein said second means includes an oscillator, the output of which is phase-modulated by data stored in said second layer, and said third means includes a demodulator for demodulating said modulated output.

30. In a data communications system including an encoder/ decoder for encoding and decoding communicatable signals, a transceiver for transmitting and receiving encoded signals, and means for communicatively coupling said encoder/decoder and said transceiver, an improved means for communicatively coupling comprising:

a variable reluctance magnetic recording/reproduction apparatus including

a magnetic recording medium having at least a first layer of a highly coercive magnetic material for receiving and storing signals, and at least a second layer of a magnetically permeable shunt material, said first and second layers being separated by an exchange-breaking layer;

a magnetic transducing means including a magnetically permeable core with a transceiving gap, and an electrically conducting coil wrapped about at least a portion of said core, said transducer being positioned relative to a surface of said recording medium for transferring signals through said second layer for storage in said first layer;

means for moving said recording medium and said transducer with respect to each other;

means for generating a sense field in said transducer which partially saturates a region of said shunt material disposed directly below said gap during signal transfers from said recording medium to said transducer;

means for generating a write field in said transducer which completely saturates a region of said permeable shunt material disposed directly below said gap during signal transfers from said transducer to said recording medium, whereby data stored in said medium may be encoded and recovered in binary or non-binary form;

first means for connecting said transducing means to said encoder/decoder; and

second means for connecting said transducing means to said transceiver.

31. In a data communications system as recited in claim 30 wherein the signals are stored in said first layer with their axes of magnetization substantially parallel to the plane of the recording medium.

32. In a data communications system as recited in claim 30 wherein the signals are stored in said first layer with their axes of magnetization substantially perpendicular to the plane of the recording medium.

33. In a data communications system as recited in claim 30 wherein said magnetic recording medium includes a planar substrate and wherein said first layer, said exchange-breaking layer and said second layer are formed on a surface of said substrate.

34. In a data communications system as recited in claim 33 wherein the surface of said planar substrate on which said first layer, said exchange-breaking layer, and said second layer are formed has an isotropic texture.

35. In a data communications system as recited in claim 30 wherein said magnetic recording medium includes a plurality of layers of magnetic material having a coercivity of at least 1000 oersteds.

36. In a data communications system as recited in claim 30 wherein said magnetic recording medium includes a plurality of layers of shunt material having a coercivity of less than 200 oersteds.

37. In a data communications system as recited in claim 36 wherein said magnetic recording medium includes a plurality of layers of magnetic material having a coercivity of at least 1000 oersteds.

38. In a data communications system as recited in claim 30 wherein said first layer, said exchange-breaking layer and said second layer are formed in a surface of a planar substrate.

39. In a data communications system as recited in claim 34 wherein no permeable shunt layer substantially interacts with any magnetic recording layer through intimate atom-to-atom magnetic exchange coupling.

40. In a data communications system as recited in claim 30 wherein said exchange-breaking layer is formed by a relatively thin layer of non-magnetic material.

41. In a data communications system as recited in claim 30 wherein the materials and relative thicknesses of said permeable shunt layer and each said magnetic recording layer are such that flux from recorded transitions in said magnetic recording layer is substantially shunted by said permeable shunt layer.

42. In a data communications system as recited in claim 30 wherein the flux required to partially saturate a region of said shunt material to its optimum operating point is less than the flux required to erase magnetic signals stored in the magnetic material.

43. In a data communications system as recited in claim 30 wherein the means for generating a sense field in said transducer includes an electrically conducting coil wrapped about a portion of said core.

44. In a data communications system as recited in claim 30 wherein said magnetic recording medium is included in a fixed or removable magnetic disk.

45. In a data communications system as recited in claim 30 wherein said magnetic recording medium is included in a magnetic tape.

46. In a data communications system as recited in claim 30 wherein said magnetic recording medium is included in a magnetic card.

47. In a data communications system as recited in claim 30, wherein said magnetically permeable core is connected to said encoder/decoder by said first means, and wherein said transducing means includes another magnetically permeable core connected to said transceiver by said second means.

48. In a data communications system as recited in claim 30 wherein said transducer has an inductive reactance that changes in proportion to the permeability of a variable reluctance element formed by the portion of said layer of permeable shunt material bridging the gap of said transducer, and wherein said means for generating a sense field in said transducer includes

first means for applying a DC-bias current to said coil to cause partial saturation of said variable reluctance element,

second means for generating an alternating current for addition to the DC-bias current applied to said coil, and

third means for monitoring changes in the inductive reactance of said transducer caused by data stored in said second layer.

49. In a data communications system as recited in claim 48 wherein said second means includes an oscillator, the output of which is frequency-modulated by data stored in said second layer, and said third means includes a demodulator for demodulating said modulated output.

50. In a data communications system as recited in claim 48 wherein said second means includes an oscillator, the output of which is phase-modulated by data stored in said second layer, and said third means includes a demodulator for demodulating said modulated output.

51. In a data communications system including an encoder/ decoder for encoding and decoding communicatable signals, a transceiver for transmitting and receiving

encoded signals, and means for communicatively coupling said encoder/decoder and said transceiver, an improved means for communicatively coupling comprising:

a magnetic recording medium having at least one layer of magnetic material for receiving and storing magnetic signals;

a magnetic transducer including a permeable core with its gap positioned relative to the surface of said magnetic recording medium for transferring signals with respect to said recording medium;

means forming at least one layer of a permeable shunt material between said permeable core and said magnetic recording medium;

means for moving said magnetic recording medium and said magnetic transducer with respect to each other;

means for generating a sense field in said core which partially saturates the region of said permeable shunt material bridging said gap during signal transfers from the magnetic recording medium to the magnetic transducer; and

means for generating a write field in the magnetic transducer which completely saturates the portion of said shunt material bridging said gap during signal transfers from the transducer to the recording medium, whereby data stored in said medium may be encoded and recovered in non-binary form.

52. In a data communications system as recited in claim 51 wherein said layer of magnetic material is formed on a substrate and has a layer of non-magnetic material covering it, and wherein said layer of permeable shunt material is formed over said layer of non-magnetic material.

53. In a data communications system as recited in claim 51 wherein said magnetic recording medium includes a plurality of layers of magnetic material.

54. In a data communications system as recited in claim 51 wherein multiple layers of permeable shunt material are disposed between said permeable core and said magnetic recording medium.

55. In a data communications system as recited in claim 51 wherein said layer of permeable shunt material is carried by said core and bridges said gap.

56. In a data communications system as recited in claim 51 wherein said layer of magnetic material has a coercivity of at least 1000 oersteds and said layer of shunt material has a coercivity of less than 200 oersteds.

57. In a data communications system as recited in claim 51 wherein said transducer has an inductive reactance that changes in proportion to the permeability of a variable reluctance element formed by the portion of said layer of permeable shunt material bridging the gap of said transducer, and wherein said means for generating a sense field in said transducer includes

first means for applying a DC-bias current to said coil to cause partial saturation of said variable reluctance element,

second means for generating an alternating sense current for addition to the DC-bias current applied to said coil, and

third means for monitoring changes in the inductive reactance of said transducer caused by data stored in said second layer.

58. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 57 wherein said second means includes an oscillator, the output of which is frequency-modulated by data stored in said second layer, and said third means includes a demodulator for demodulating said modulated output.

59. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 57 wherein said second means includes an oscillator, the output of which is phase-modulated by data stored in said second layer, and said third means includes a demodulator for demodulating said modulated output.

60. A method of magnetically storing and retrieving electrical signals using a magnetic transducer having a physical transducing gap moving relative to a closely spaced magnetic storage medium including a highly coercive layer with respect to which signals are to be transferred through an overlaying magnetically permeable. partially saturable shunt material separated from said highly coercive layer by a thin breaking region of a non-magnetic material, comprising the steps of:

(a) storing data in said magnetic storage medium by

(i) generating a magnetic bias flux in the transducer core which fully saturates the permeable shunt material proximate the transducing gap, and

(ii) generating data flux in the transducer core corresponding to bits of data to be stored in said highly coercive layer; and

(b) retrieving data stored in said magnetic storage medium by

(iii) generating a magnetic bias flux in the transducer core which only partially saturates the permeable shunt layer proximate the transducing gap, and

(iv) sensing the data flux induced in said transducer core as said transducer passes over storage sites in which data has previously been stored.

61. A method of magnetically storing and retrieving electrical signals as recited in claim 60, wherein the bias flux is at least partially generated by the application of an alternating current to the flux-inducing windings of the core of the transducer.

62. A method of magnetically storing and retrieving electrical signals as recited in claim 61, wherein the amplitude and frequency of the alternating current applied to said transducer during data retrieval is below a level that would develop flux capable of saturating the region of the permeable material proximate the transducing gap.

63. A method of magnetically storing and retrieving electrical signals as recited in claim 62, wherein the frequency of said alternating sense current is equal to and synchronous with the frequency at which data is stored in said recording medium.

64. A method of magnetically storing and retrieving electrical signals as recited in claim 62, wherein the frequency of said alternating sense current is equal to a harmonic of, and is synchronous with the frequency at which data is stored in said recording medium.

65. A variable reluctance magnetic recording/reproduction apparatus as recited in claim 7 wherein said second means includes an oscillator, the output of which is amplitude-modulated by data stored in said second layer, and said third means includes a demodulator for demodulating the modulated output.

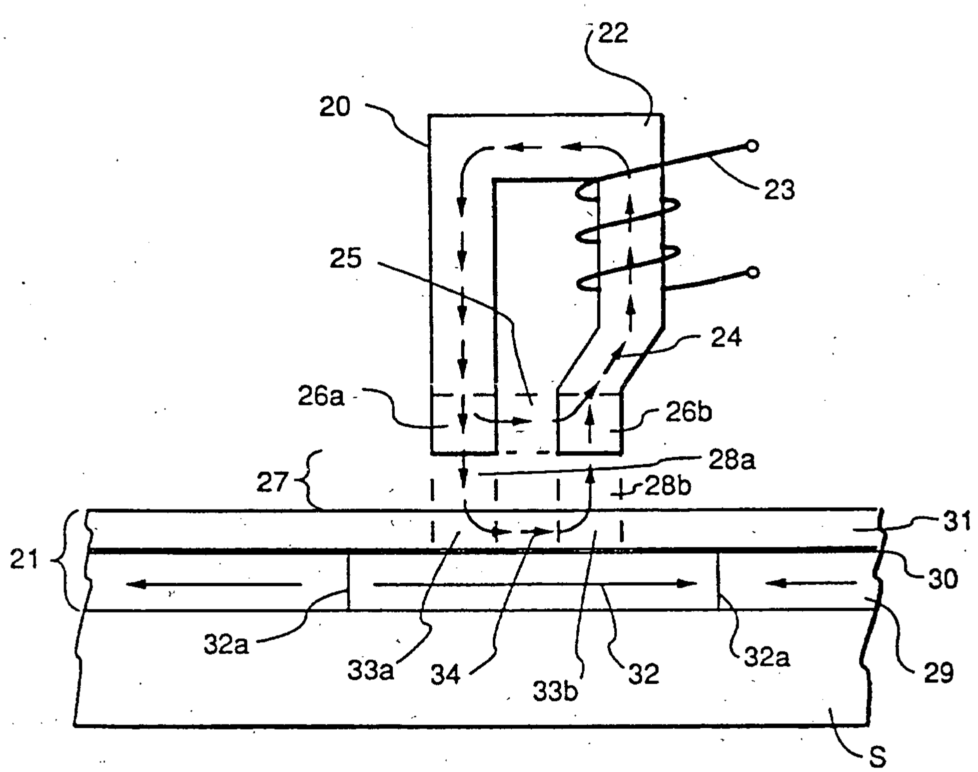

Fig. 1

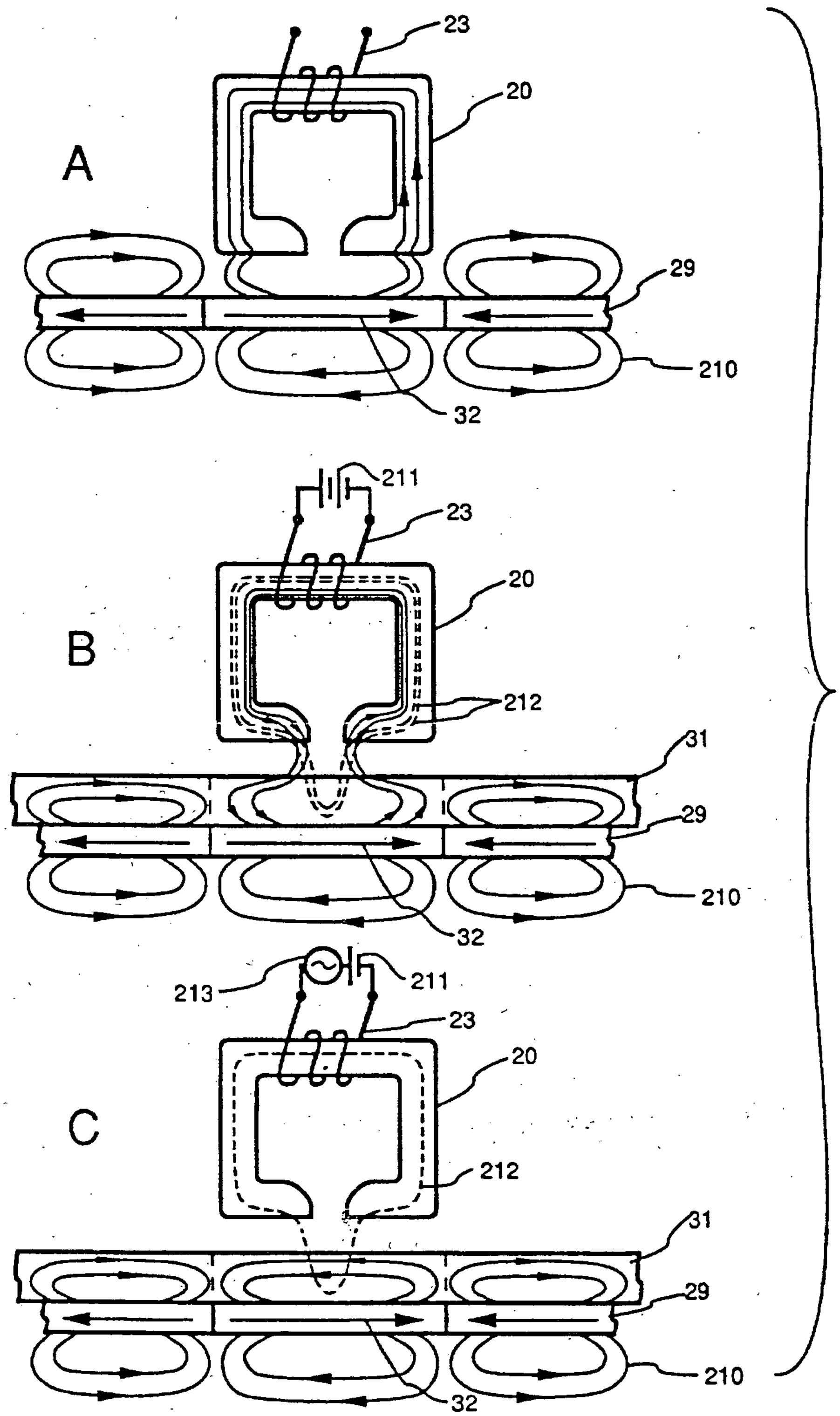
A
23
20
29
210
32
B
211
23
20
212
31
29
210
32
C
213
211
23
20
212
31
29
210
32

Fig. 1a

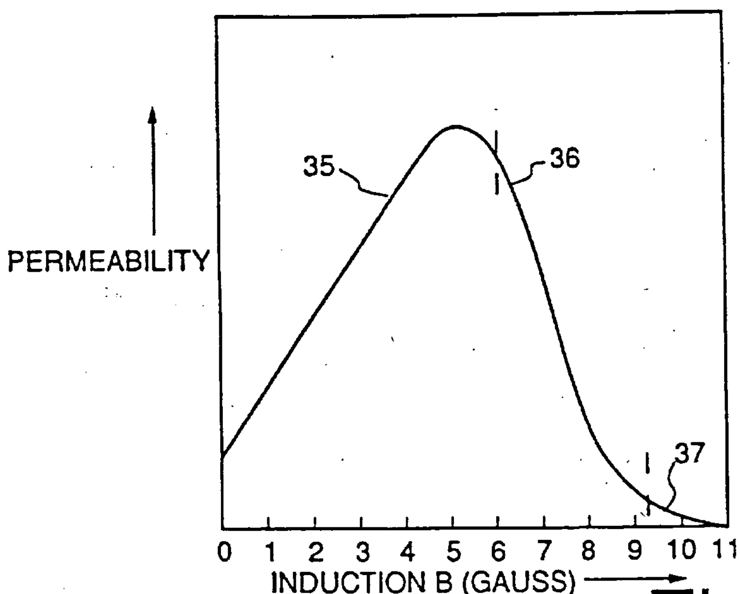
PERMEABILITY
35
36
37
0 1 2 3 4 5 6 7 8 9 10 11
INDUCTION B (GAUSS)

Fig. 2

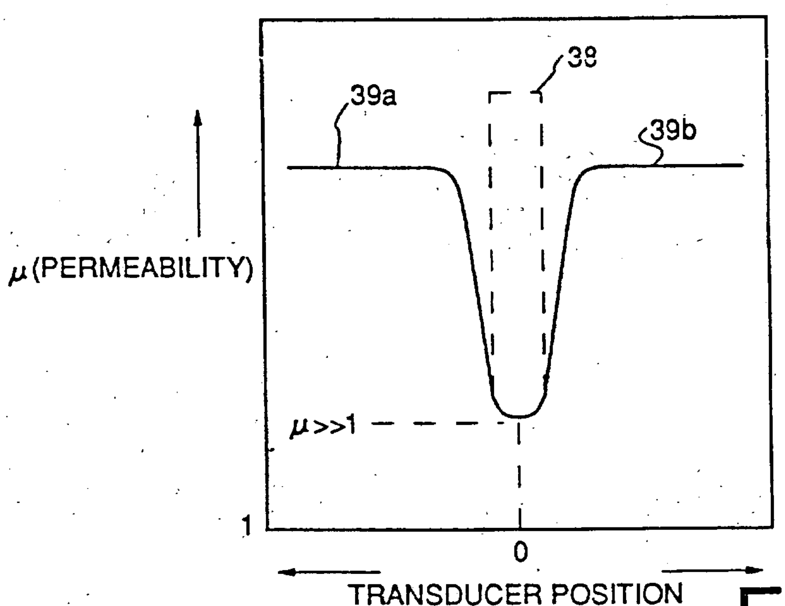
μ (PERMEABILITY)
38
39a
39b
μ>>1
1
0
TRANSDUCER POSITION

Fig. 3

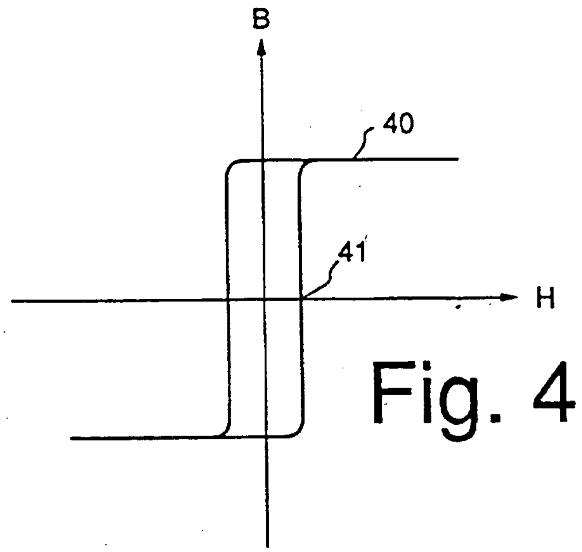

Fig. 4

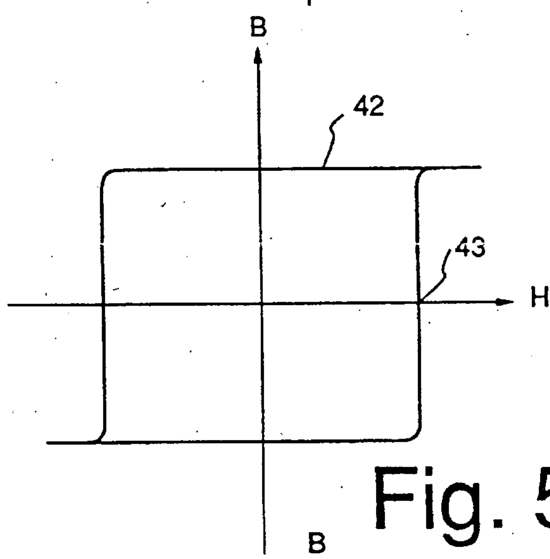

Fig. 5

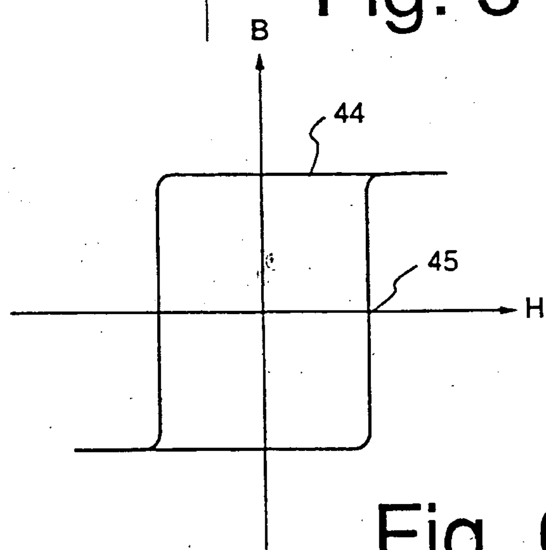

Fig. 6

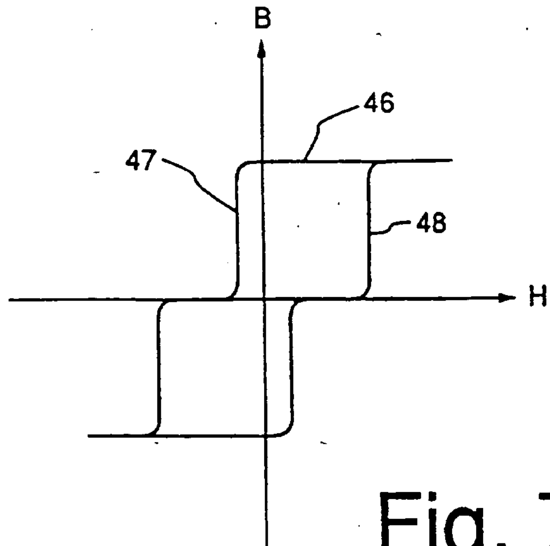

Fig. 7

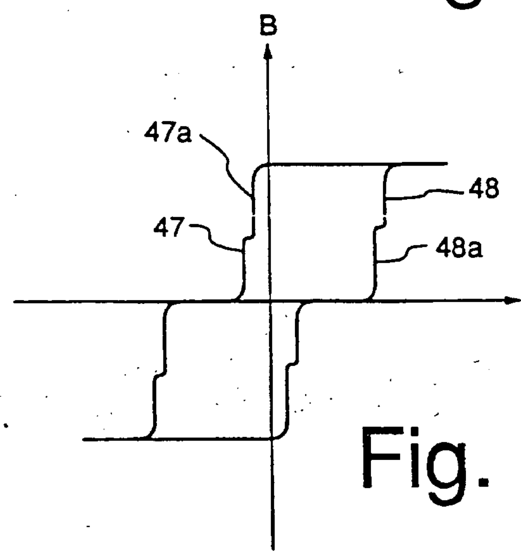

Fig. 7a

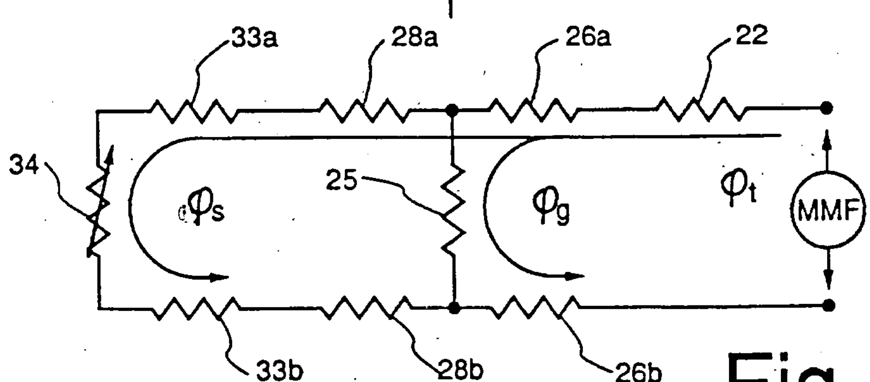

Fig. 8a

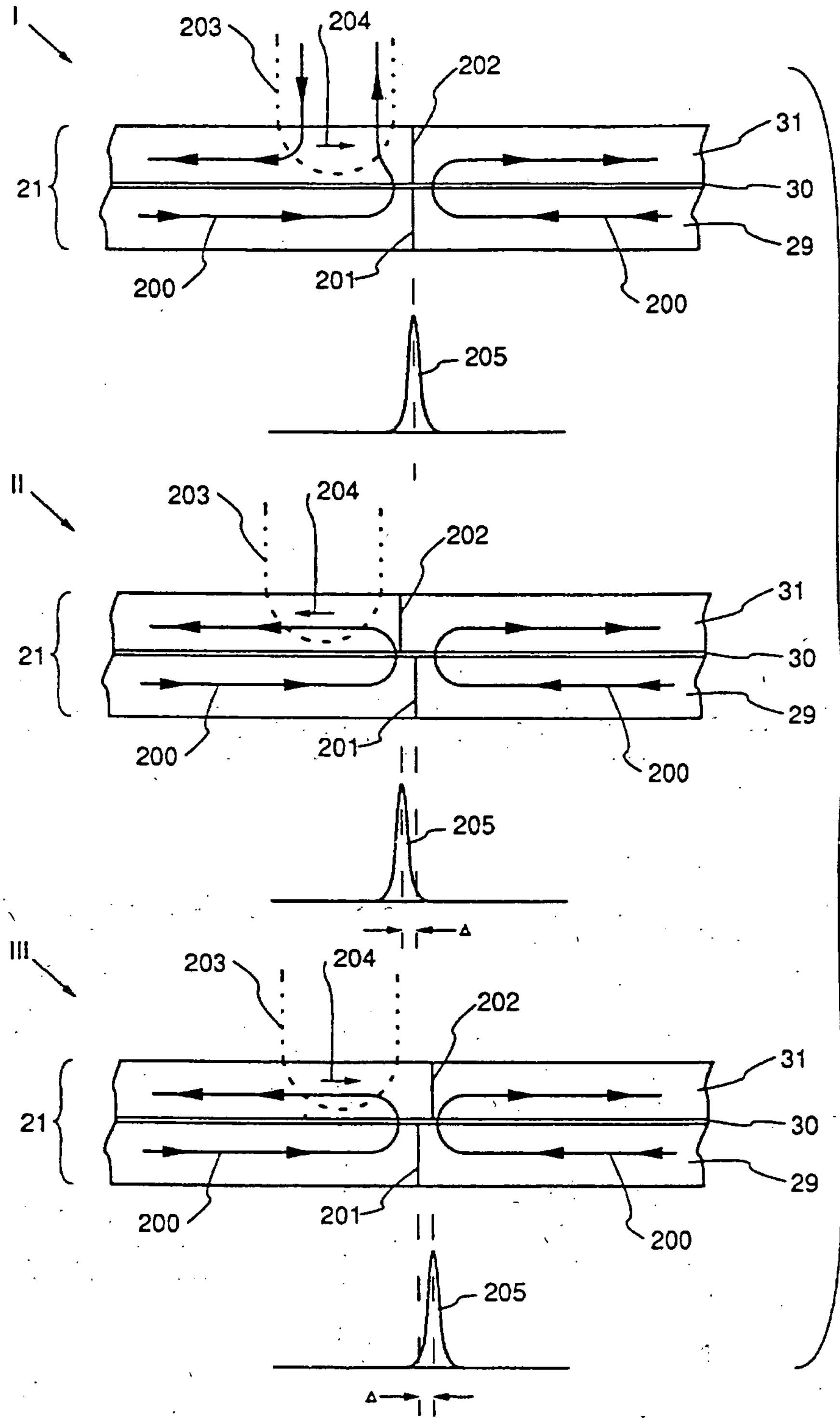
I
203
204
202
31
21
30
29
200
201
200
205
II
203
204
202
31
21
30
29
200
201
200
205
Δ
III
203
204
202
31
21
30
29
200
201
200
205
Δ

Fig. 8c

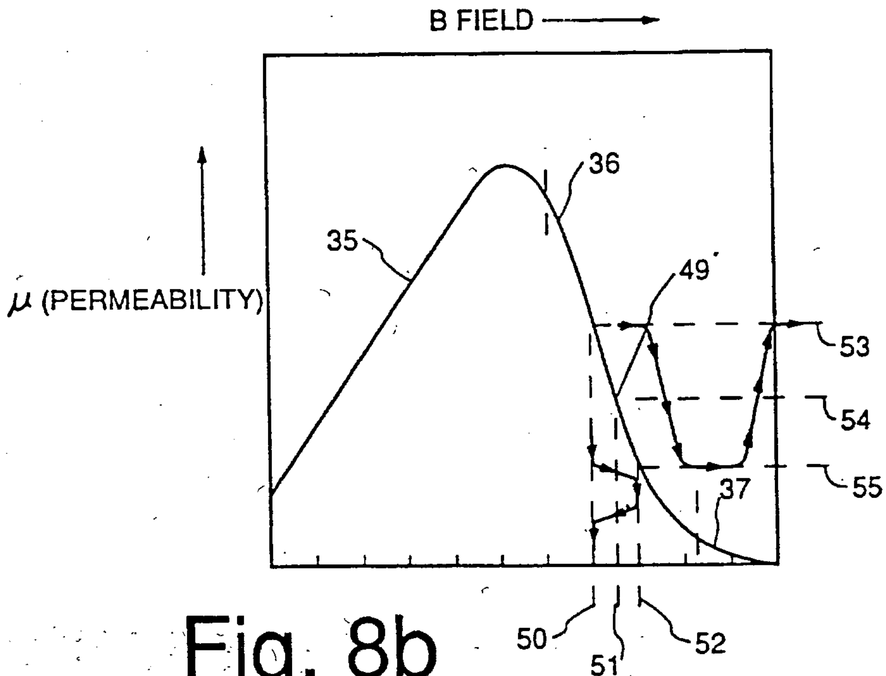
B FIELD
μ (PERMEABILITY)
35
36
37
49
50
51
52
53
54
55

Fig. 8b

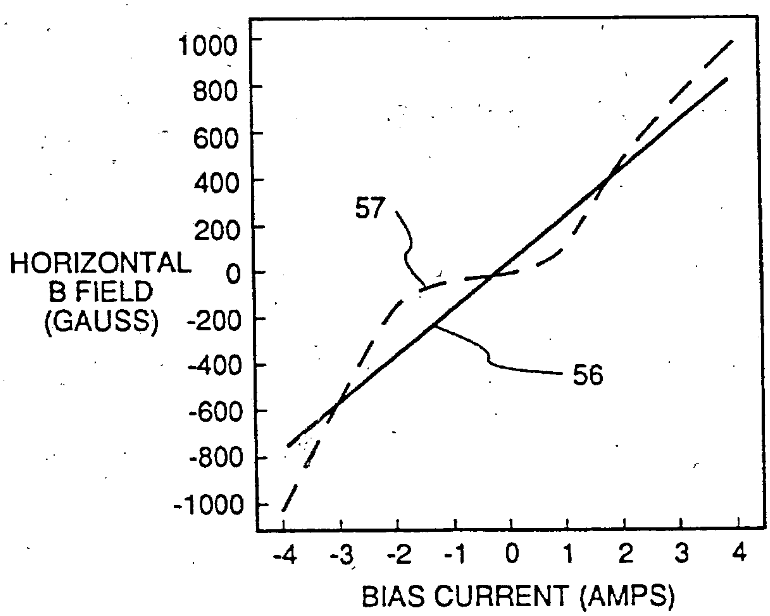
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
HORIZONTAL B FIELD (GAUSS)
57
56
-4
-3
-2
-1
0
1
2
3
4
BIAS CURRENT (AMPS)

Fig. 9a

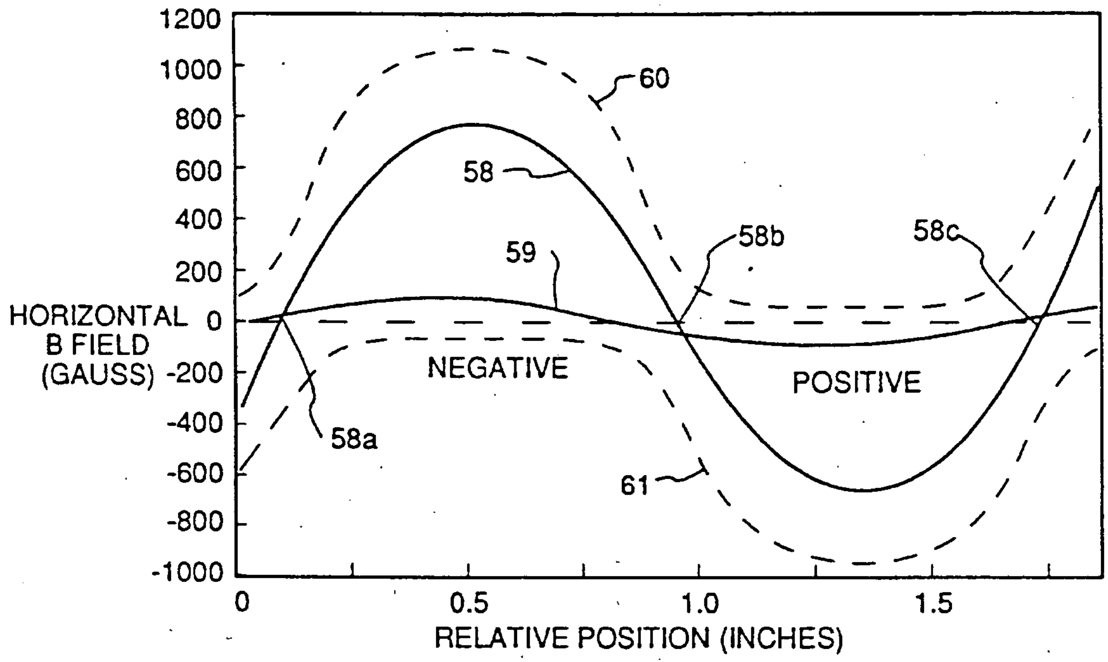
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
HORIZONTAL
B FIELD
(GAUSS)
60
58
59
58b
58c
58a
61
NEGATIVE
POSITIVE
0
0.5
1.0
1.5
RELATIVE POSITION (INCHES)

Fig. 9b

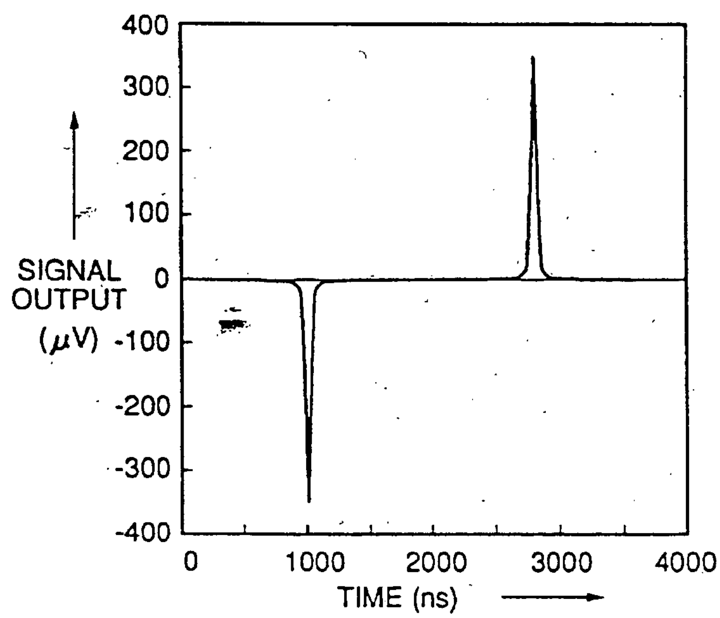
400
300
200
100
0
-100
-200
-300
-400
SIGNAL
OUTPUT
(μV)
0
1000
2000
3000
4000
TIME (ns)

Fig. 9c

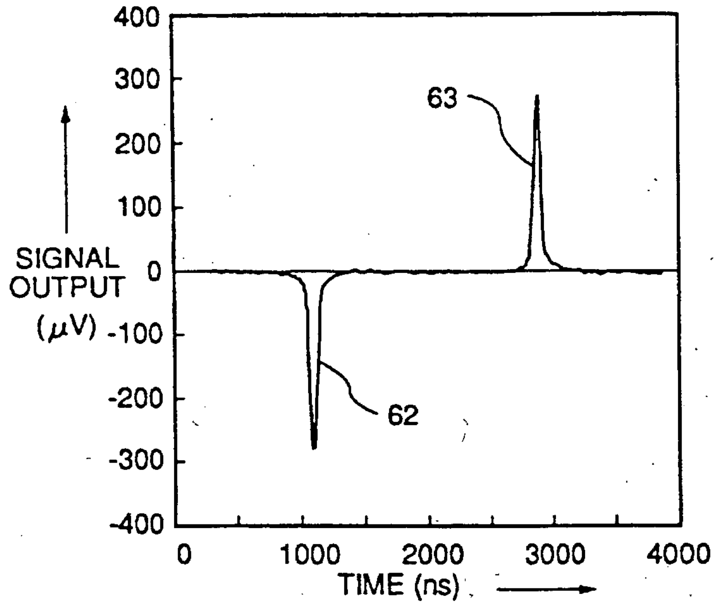

Fig. 10a

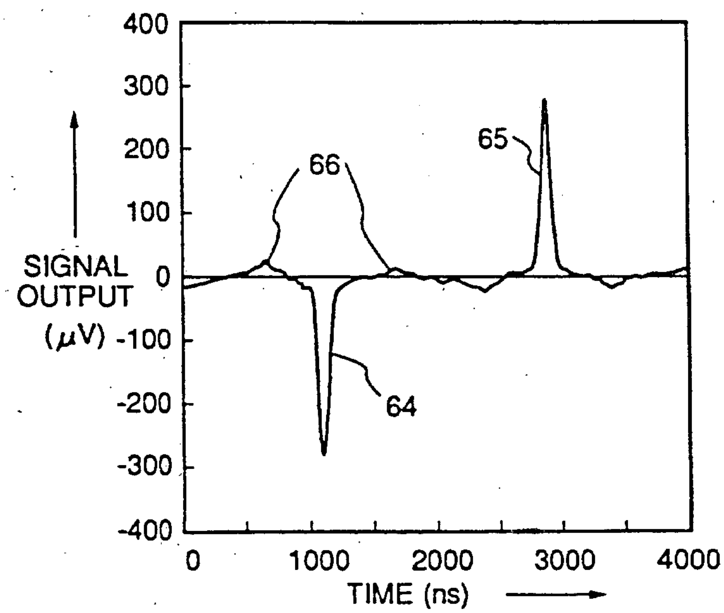

Fig. 10b

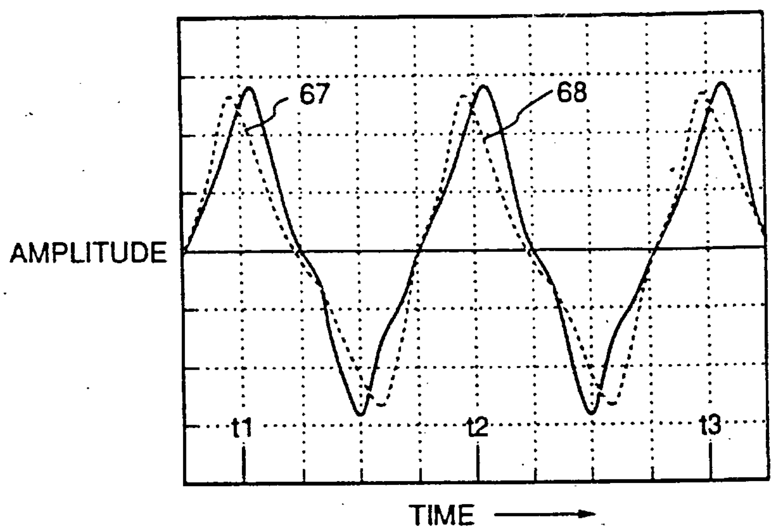

Fig. 11a

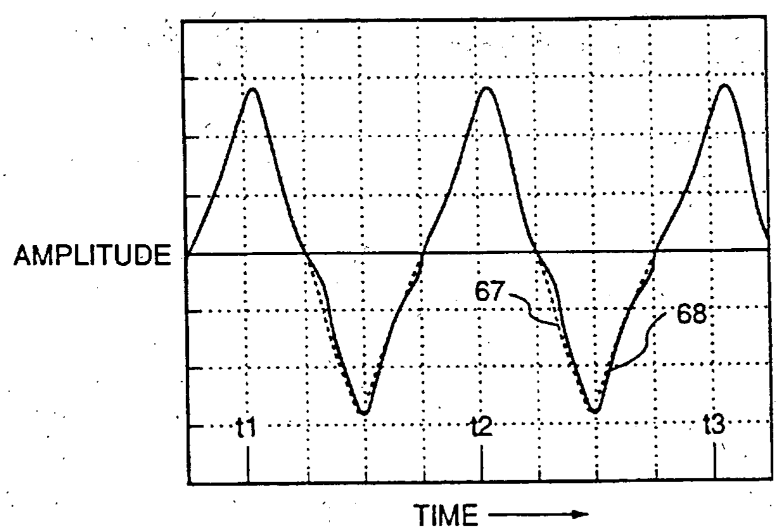

Fig. 11b

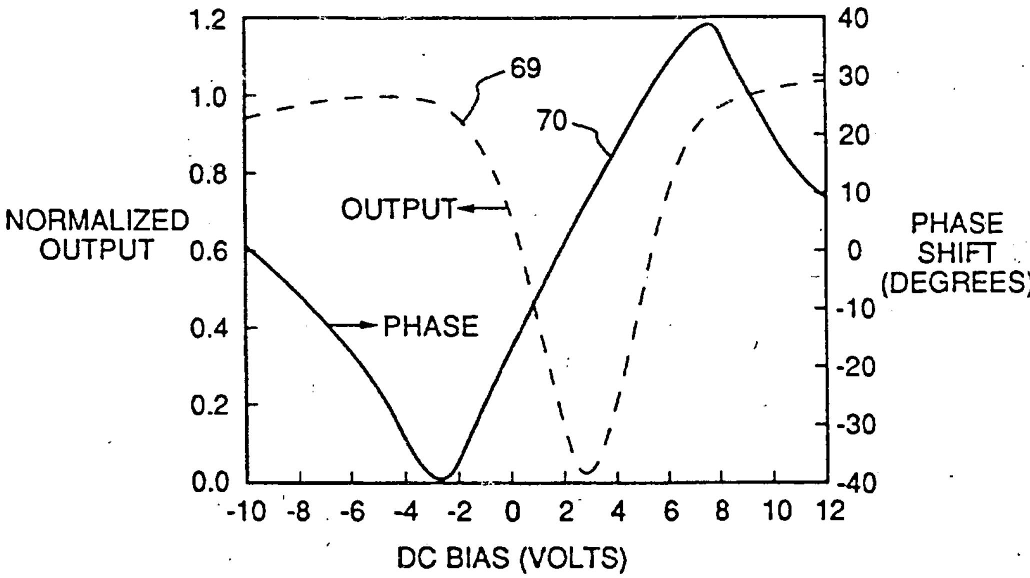

Fig. 11c

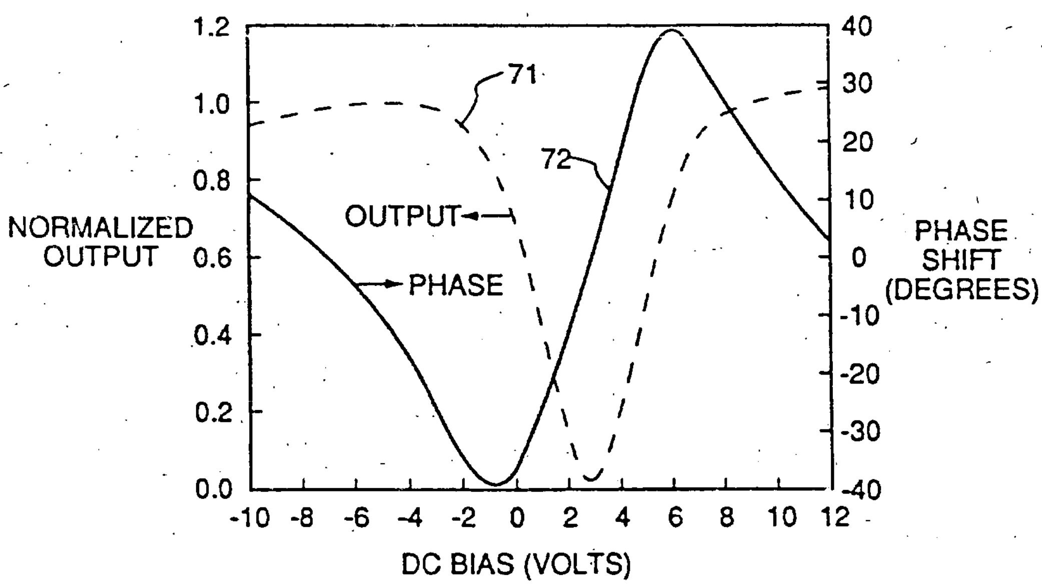

Fig. 11d

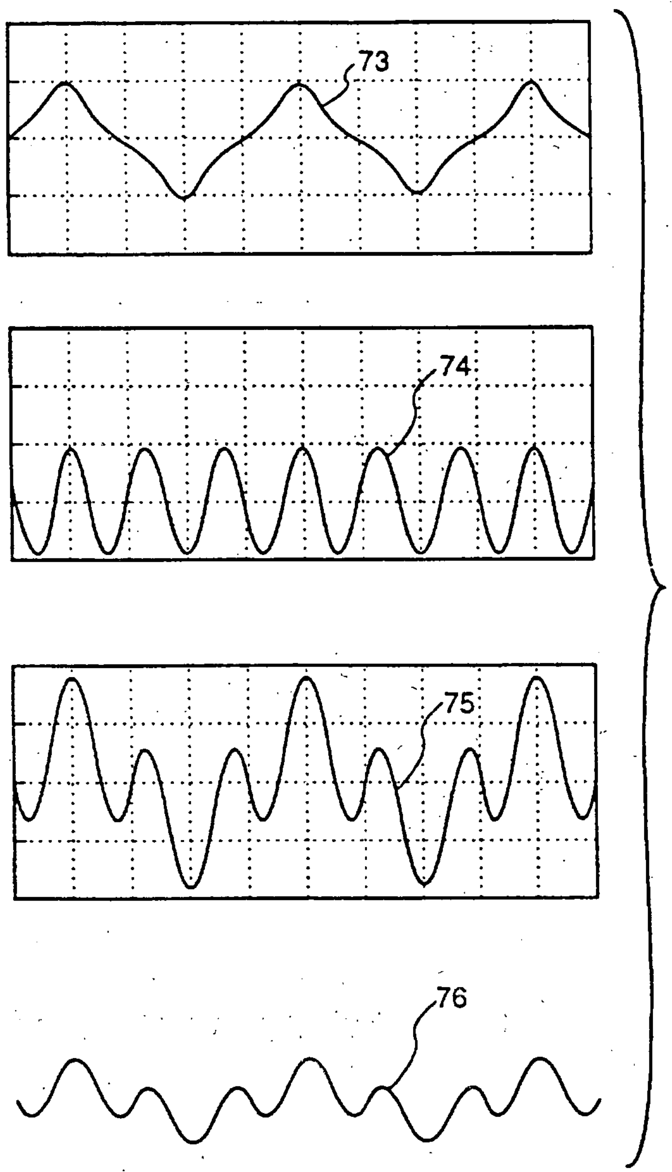

Fig. 12a

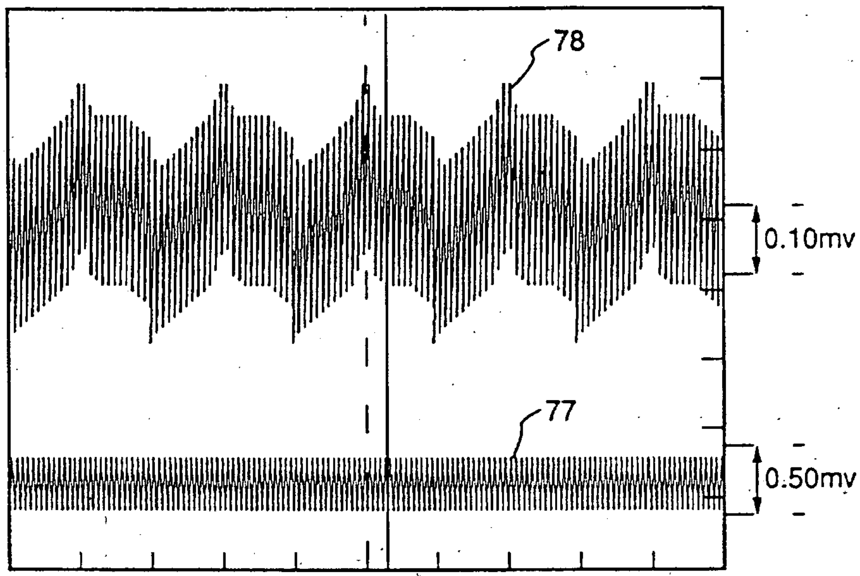

Fig. 12b

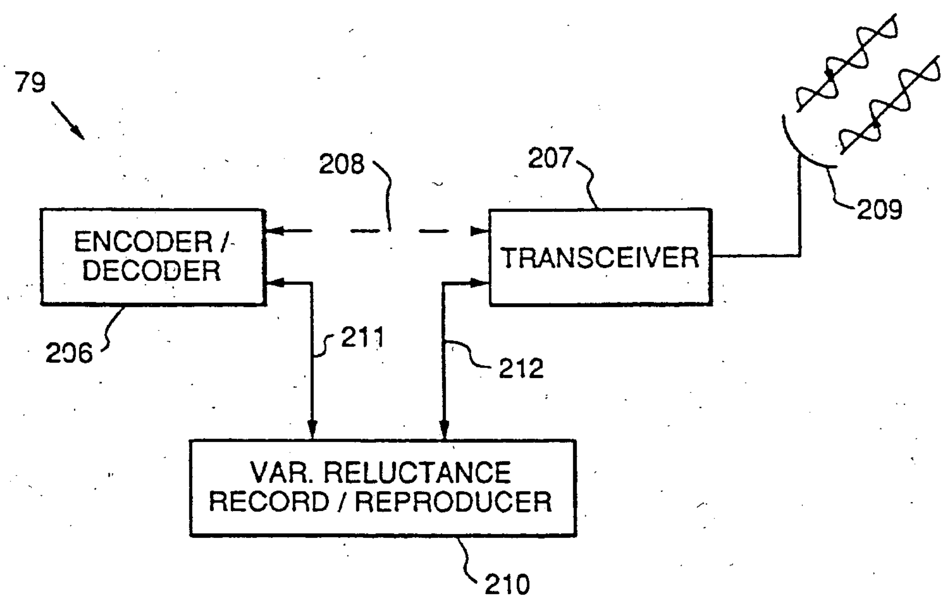

Fig. 13

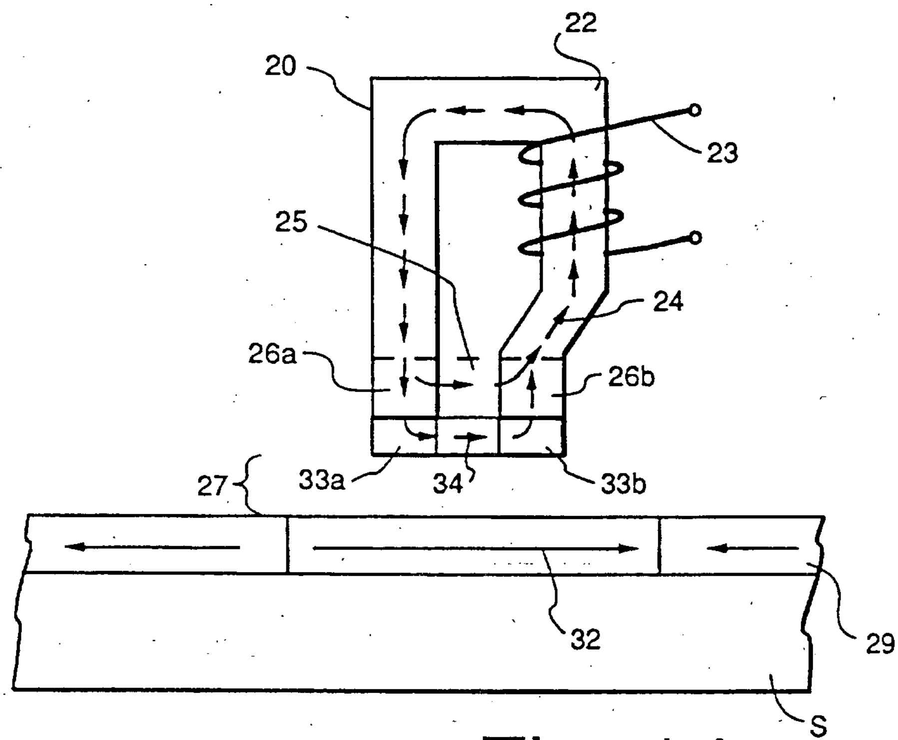
22
20
23
25
24
26a
26b
27
33a
34
33b
32
29
S

Fig. 14

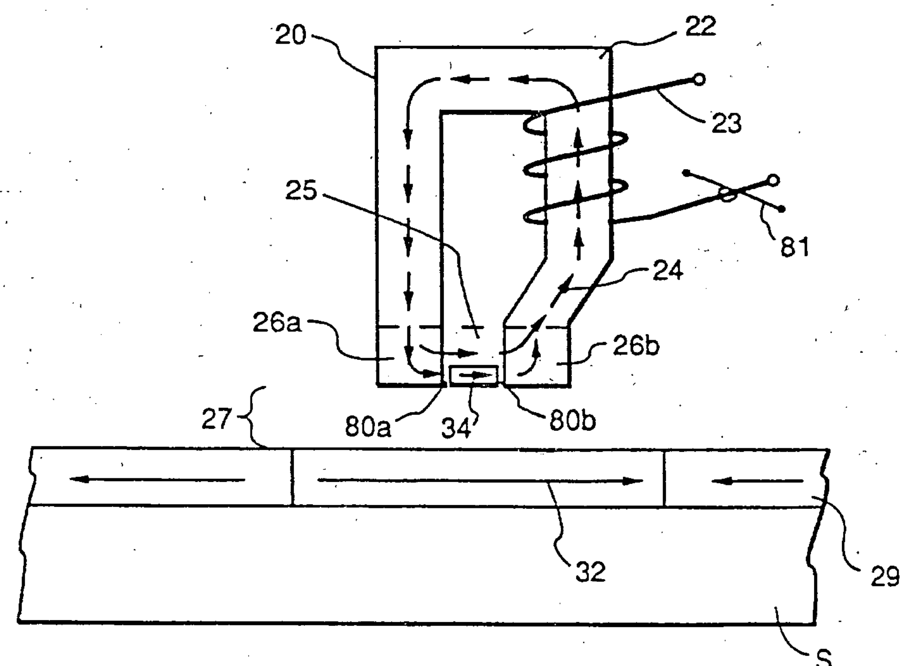
20
22
23
25
81
24
26a
26b
27
80a
34
80b
32
29
S

Fig. 15

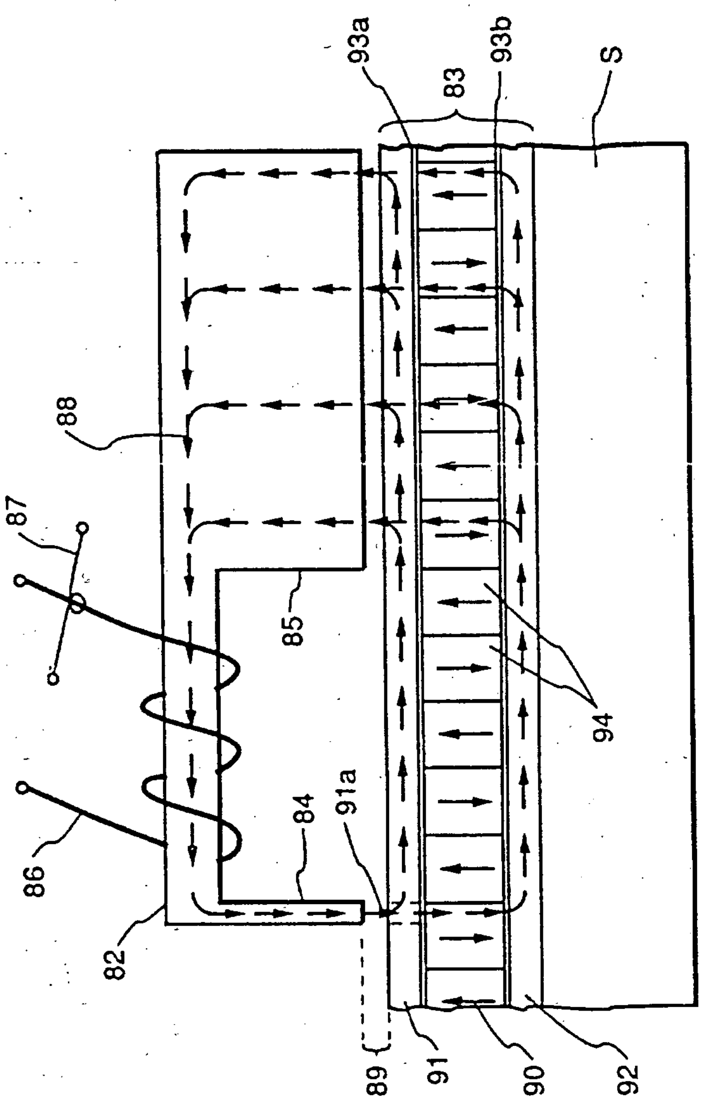

Fig. 16

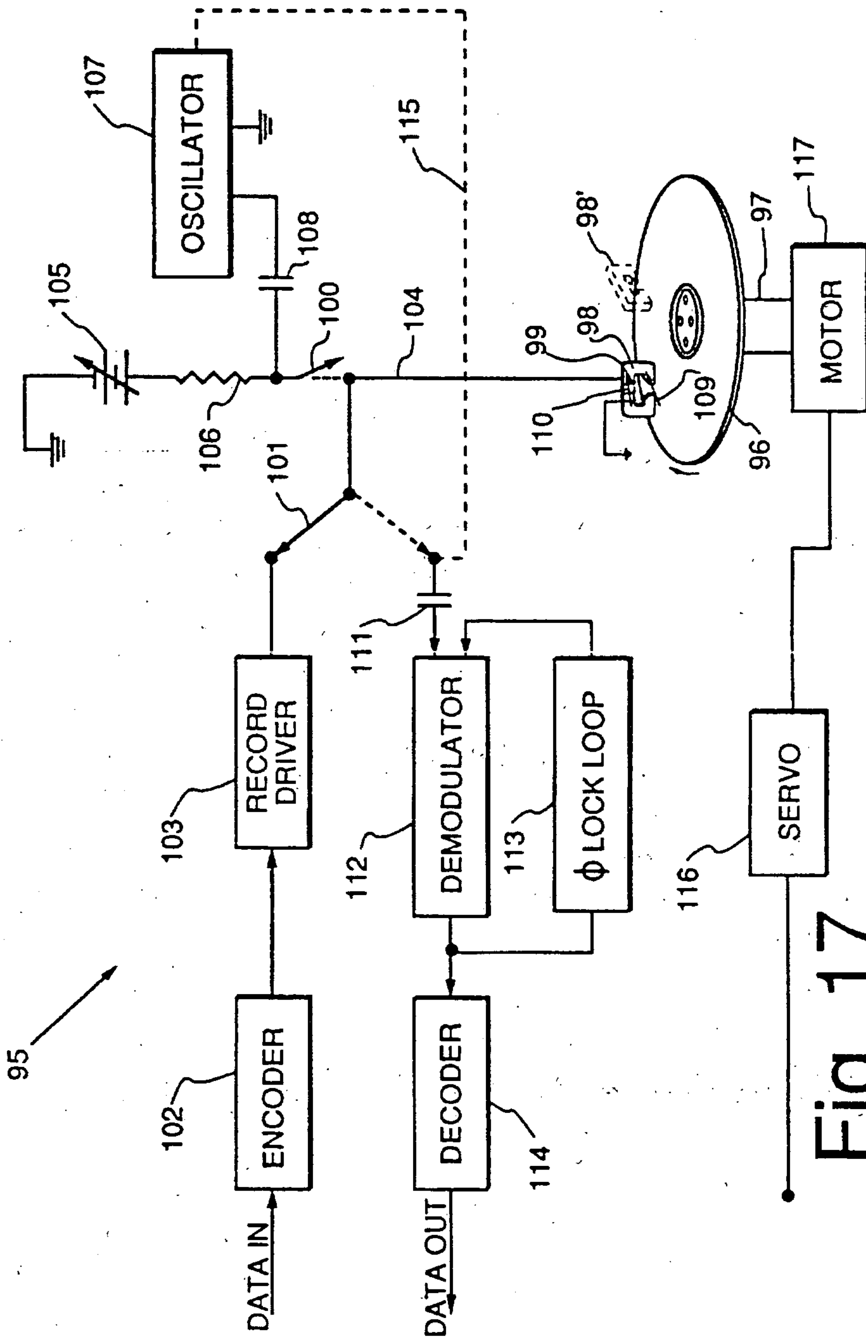
OSCILLATOR
RECORD DRIVER
ENCODER
DEMODULATOR
DECODER
ϕ LOCK LOOP
SERVO
MOTOR
DATA IN
DATA OUT
95
96
97
98
98'
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117

Fig. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/02089

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G11B 05/03
US CL : 360/066
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 360/029, 055, 066, 077.12, 115, 119, 121, 122
428/611

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 5,041,922 [WOOD ET AL] 20 August 1991, entire doc.	1, 10, 30, 51, 60
Y	US, A, 5,189,572 [GOOCH ET AL] 23 February 1993, entire document	1, 3, 10, 30, 35, 37, 43, 51, 53, 60-61
Y	WO 93/12928 [REED ET AL] 08 July 1993, entire document	1, 2, 6, 10, 30, 36, 40-41,51-52, 56, 60,

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search	Date of mailing of the international search report
04 JUNE 1996	21 JUN 1996
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer PATRICK GEORGE WAMSLEY Telephone No. (703) 308-0956

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/02089

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-3, 6, 10-12, 15-17, 19-21, 23, 30-32, 35-37, 40-41, 43, 47, 51-53, 56, and 60-65

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

Species I. Claims 2, 20, 40, 52, and 60-65, with a non magnetic layer.
Species II. Claims 7-9, 27-29, 48-50, 57-59, and 65, with DC bias.
Species III. Claims 5 and 55, with a core carried shunt bridging the gap.
Species IV. Claims 4 and 54, with multiple shunts between core / medium.
Species V. Claims 24 and 44. with a magnetic disk medium.
Species VI. Claims 25 and 45, with a magnetic tape medium.
Species VII. Claims 26 and 46, with a magnetic card medium.
Species VIII. Claims 13-14, 18, 33-34, 38, 39, with a planar substrate.
Species IX. Claims 22 and 42, with partial saturation flux less than erasure flux.
Currently, claims 1, 3, 6, 10-12, 15-17, 19, 21, 23, 30-32, 35-37, 41, 43, 47, 51, 53, and 56 are generic.

The inventions listed as Species I-IV do not meet the requirements for Unity of Invention for the following reasons: The listed species of inventions lack unity because there are no common "special techinical features" with each claimed species. Species I requires a non-magnetic exchange breaking layer. Species II requires DC bias application. Species III requires a permeable shunt layer carried by the core and bridging the gap. Species IV requires multiple permeable shunt layers disposedbetween the core and medium. Species V, VI, and VII respectively require a magnetic disk, a magnetic tape, and a magnetic card as storage media. Species VIII requires a planar substrate. Species IX requires a smaller flux for partial saturation than for erasure of data.